UNIVERSIDADE DE LISBOA
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Assessing energy efficient retrofitting process

Decision Support Systems analysis

Ana Isabel Mestre Lopes

Mestrado Integrado em Engenharia da Energia e do Ambiente

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Dissertação de Mestrado em Engenharia da Energia e do Ambiente

Trabalho realizado sob a supervisão de

Jesús Rosales Carreón (Utrecht University)

Marta João Nunes Oliveira Panão (FCUL)

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Abstract

Buildings are amongst the major energy consumers in Europe, accounting for 40% of the total primary energy consumption. The building sector holds the largest potential to achieve energy savings through retrofit. Although the need of renovating the existing building stock is acknowledged and the settled targets to achieve in the near future are ambitious, there are several barriers hindering the increase the rate and depth of the refurbishment projects. A major hindrance occurring in the design phase is the lack of tools to support the retrofit decision making process.

The present research focuses on Decision Support Systems (DSSs) as tools developed to enhance the analysis of the impacts of retrofit measures in buildings, evaluate a vast range of factors and use iterative processes to reach the most feasible and adequate retrofit solution for a particular building. There are many DSSs for retrofit available which have been developed recently and thus the number of research studies analysing them is limited. Therefore, this research focuses on enhancing the current limited research on DSSs for retrofit. To this end, we have compared and analysed five European free-software DSSs: *BioRegional*, *Generation*, *ICE (2.0.8)*, *Retrofit Advisor* and *TABULA*.

A comparative method was developed in order to analyse six dimensions of the DSSs: technical, input, output, energy, environmental and economical. We concluded that standardized methods are not implemented. The indicators developed to compare the dimensions of the DSSs can be regarded as a baseline comparison for the retrofit decision making process amongst other DSSs. The adoption potential of the DSSs was also compared and we concluded that as the DSSs currently exist, they will hardly reach the user and if they do, issues of complexity and compatibility may discourage the adoption of the DSS. Suggestions were made to a more complete and standardized European DSS.

Keywords: Sustainable Cities, Energy Efficiency, Retrofitting, Decision Support Systems, Comparative Research.

Resumo

Os edifícios encontram-se entre os maiores consumidores de energia na Europa, representando 40% do consumo de energia primária total. Por outro lado, é também o sector que apresenta o maior potencial de poupança energética através de remodelação. Apesar da urgência de remodelação do *stock* existente ser reconhecida, alguns obstáculos continuam a impedir o aumento da taxa e extensão dos projectos de remodelação. Um dos maiores obstáculos na fase conceptual é a ausência de ferramentas que facilitem o processo de decisão.

O presente estudo foca-se em Sistemas de Suporte à Decisão (SSDs) como ferramentas desenvolvidas para melhorar a análise dos impactos das medidas de remodelação nos edifícios, analisar simultaneamente um grande número de variáveis e usar processos iterativos de forma a selecionar a solução mais viável e adequada para um edifício particular. Existem vários SSDs para remodelação de edifícios disponíveis que foram desenvolvidos recentemente. Por essa razão o número de estudos científicos existentes que os analisam é limitado. Consequentemente, a presente dissertação pretende reforçar a investigação em SSDs para remodelação eficiente de edifícios. Foram comparados e analisados cinco SSDs Europeus de *software* livre: *BioRegional*, *Generation*, *ICE (2.0.8)*, *Retrofit Advisor* and *TABULA*.

Foi desenvolvido um método de comparação de forma a analisar seis dimensões dos SSDs: técnica, *input*, *output*, energética, ambiental e económica. Concluímos que métodos padronizados não estão implementados. Os indicadores desenvolvidos para comparar as dimensões dos SSDs podem ser considerados como uma base de referência para a comparação entre outros SSDs. O potencial de adoção dos SSDs foi também comparado e concluímos que o utilizador terá dificuldade em encontrá-los e, uma vez experimentados, os problemas derivados da complexidade e compatibilidade dos SSDs podem desencorajar o utilizador à sua adoção. Por último, foi possível sugerir melhorias para um SSD mais completo e uniformizado na Europa.

Palavras-chave: Cidades Sustentáveis, Eficiência Energética, Remodelação eficiente de edifícios, Sistemas de Suporte à Decisão, Análise Comparativa.

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Acronyms

BEM	Building Energy Model
CFD	Computational Fluid Dynamics
CO_2	Carbon Dioxide
DHW	Domestic Hot Water
DSS	Decision Support System
ECM	Energy Conservation Measure
EMCS	Energy Management and Control System
EPB	Energy Performance of the Building
EPBD	Energy Performance of Buildings Directive
EPC	Energy Performance Certificate
EC	European Commission
EU	European Union
GHG	Greenhouse Gas
GWP	Global Warming Potential
HDD	Heating Degree Days
HVAC	Heating, Ventilation and Air-conditioning
IEA	International Energy Agency
KPI	Key Performance Indicator
LED	Light-Emitting Diode
MCDA	Multi Criteria Decision Analysis
NO_x	Nitrogen Oxides
NZEB	Nearly Zero-Energy Building
RES	Renewable Energy Sources
SO_2	Sulphur Dioxide

1. Introduction

The present chapter introduces the research topic of this study. Section 1.1 discusses the global acknowledgment of the need of sustainability, especially with respect to the building environment. Section 1.2 argues the relevant role of Decision Support Systems (DSSs) for building retrofit. The scope of the present research and the research questions are presented in Section 1.3 and the methodology followed to answer the questions is described in Section 1.4. Finally, Section 1.5 presents the structure of this study and provides the summarized content of each Chapter.

1.1 Building environment sustainability

Since the first oil crisis in 1973 the developed countries have started to think seriously about the development model of their societies. They started looking for solutions towards a sustainable development, one capable of ensuring future generations access to the same resources we have in present time, in order to meet their needs. Topics like energy consumption, renewable energies and energy efficiency became a priority for many developed countries. Currently, international communities are making large compromises to increase their energy efficiency as well as to increase energy production from renewable energies towards a sustainable world.

The percentage of population living in cities is increasing since the 1950's. During 2011, around 73% of the total European population lived in urban areas and it is expected to grow to 82% in 2050, although urban annual growth rate is expected to slow down (United Nations, 2013). In the same way, urban development is expected to continue to increase and so is total energy consumption. Thus, cities represent one of the priorities to reach sustainability. Focusing on cities can help to reduce greenhouse gas (GHG) emissions, mainly carbon dioxide (CO_2), and to reduce energy consumption. Amongst the major energy consumers sectors, buildings account for 40% of primary energy consumption in most countries of the world (World Business Council for Sustainable Development [WBCSD], 2008). In the last years, governments and international organizations engaged a serious effort to improve energy efficiency in buildings. European Union (EU) has committed, on a short-term plan, to increase energy efficiency by 20% and decrease GHG emissions by 20% until 2020, in an ambitious project started in 2007, entitled "Energy 2020". One of the sectors with the largest potential identified for achieving these energy savings was the existing building stock. In a long-term plan, EU has settled the target of reducing GHG emission levels by 80-95% by 2050[1]. Considering that as a single contributor buildings represent the biggest share of European CO_2 emissions (about 36%), it is then clear that a major effort to improve building energy efficiency is needed.

According to Ma, Cooper, Daly, & Ledo (2012), the replacement rate of existing buildings by the new-build is 1,0 - 3,0% per annum, which places the existing buildings as the major energy consumers. Furthermore, 75% of the total European building stock is residential, with roughly 40% of them built before 1960 (Buildings Performance Institute Europe [BPIE], 2011). Konstantinou and Knaack (2013) alert to the fact that thermal insulation of building envelopes only became mandatory by regulation, in most countries, after the 1970's. They also state that although the structural life of a building exceeds 60 years, building envelope starts to show signs of obsolescence only after 20 or 30 years. Consequently, it is clear the European building stock is in great need of refurbishment and if one aims to reduce energy consumption and enhance sustainable cities, energy efficient retrofitting has to be promoted rapidly. Therefore this research will focus on existing residential buildings due to their largest quantity and potential for energy savings.

Beyond the environmental benefit in urban areas, the renovation of the existing building stock not only represents a considerable improvement in indoor thermal comfort conditions but also a significant decrease of final energy consumption, resulting also in money savings for tenants and building owners. On the other hand it also represents a low cost option to reduce CO_2 emissions and has the

[1] The reduction aimed by 2050 refers to the 1990's level of GHG emissions.

advantage of stimulating European economy, increasing economic activity and enhancing EU leadership in sustainable refurbishment (Næss-Schmidt, Hansen, & Danielsson, 2011).

Building energy regulation and energy labelling have become important practices in recent years. By establishing minimum requirements for energy use in buildings, energy regulations ensure energy is used in an efficient way and that energy consumption is reduced while ensuring comfort levels. By assigning a label to a building that corresponds to its energy performance, energy labelling represents an accurate way of comparison energy performance between different buildings, cities and countries. EU has implemented an energy certification of buildings in which it obliges all state members to ensure an Energy Performance Certificate (EPC) to every new building and to those who are rented or sold. With EPC, it would be expected that building owners and buyers will become more aware and interested in the energy performance of their buildings. In the same way, it would also be expected that the demand for buildings with higher performance increases and that it would stimulate owners to refurbish their buildings in order to increase their performance. However, in most cases there is a lack of knowledge on how to refurbish an existing building taking into account energy efficient as a priority. Neither the building owners nor the refurbishment companies are aware of the more efficient and adequate retrofit measures and technologies to apply in each different building. Financial factors represent another barrier to the implementation of retrofit projects. They can either influence the willingness to proceed with the project or even the depth of the project. To some extent, these barriers are the result of the lack of detailed information and evaluation of the impacts of retrofit measures. Without access to expertise in the retrofit domain the decision making process is hindered at several levels. DSSs can improve to a big extent the quality of the decision making process by providing a comprehensive analysis of the energy, environmental and economic impacts of different retrofit measures.

1.2 Decision Support Systems for retrofit

Decision support systems aim to facilitate the solution of problems regarding a certain knowledge domain. They can be defined as “A computer program that provides information in a given domain of application by means of analytical decision models and access to databases, in order to support a decision maker in making decisions effectively (…)“ (Klein, & Methlie, 1995, p.112). According to Keen & Morton (1978) they are systems that complement human problem solving and enhance decision making effectiveness. Thus, in a complex multivariable environment as sustainable innovation domain is, these support systems are extremely relevant to facilitate the system approach to the best solutions. In the particular case of building refurbishment they seem to enhance policies by facilitating their real life application and connecting buildings renovation with EPC. In addition they can make multiple analyses of different renovation technologies along with the economic analysis (e.g. investment, payback) which results in different refurbishment scenarios. All in all, the application of DSSs in refurbishment process serve as technical and financial support to a decision maker to choose the more appropriate strategy for a particular building. The DSS should provide enough information elements so the user can take an informed decision instead of deciding the solution for the user.

The definition of an intervention strategy constitutes the crucial part of the refurbishment process (Genre, Flourentzos, & Stockly, 2000). The design phase is a complex process that depends on several factors and thus, has several solutions (retrofit scenarios). Factors such as: the physical condition of the building and its thermal behaviour, the available retrofit technologies, the goals and targets of the user or the financial viability of the project, influence the type and extension of the project to implement. They must be evaluated together and therefore, make of each retrofit project a unique and complex optimisation problem. DSSs are of great value because they are capable of using iterative processes to reach the most suitable solution for a particular case. Furthermore, they spare time in calculations that would take too long manually and allow a quick comparison of different scenarios which can open new perspectives.

In recent years, several DSSs for evaluating energy efficient retrofit measures have been developed and are available to general public. They can provide the analysis of the building energy performance and calculate the impacts of several energy efficient retrofit scenarios. However, there are dozens of

DSSs available, developed by different stakeholders, targeted for specific users and that vary to a great extent in their capabilities and analysis. The complexity of the analysis performed and the interface with the user are also extremely varied amongst the DSSs.

1.3 Scope of the research

When working in building refurbishment domain the problem consists in how to assess the refurbishment process, that is to say how to evaluate the building and choose the best retrofit concept for a specific building. Decision support systems are of great value to facilitate and accelerate this process. A representation of the refurbishment environment is shown in Figure 1. The process of generating retrofit scenarios is dynamic and results from an interaction with the user. As Figure 1 shows, the scenarios are constructed based on the building input data given by the user, within the limitations of the DSS. Then the user receives the output data generated by the DSS and is able to analyze and compare the scenarios. The user is then able to make a decision on the intervention strategy: either by choosing one of the suggested scenarios or by repeating the process to improve the scenario according to his targets and goals.

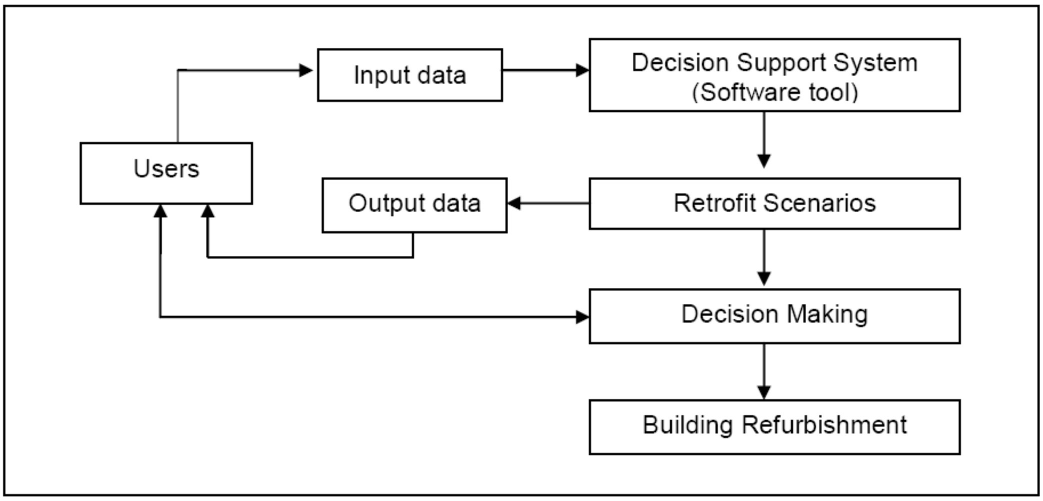

Figure 1 - System approach for the building refurbishment environment.

However, this process is not standardized, neither in the quantity and quality of input required and output provided. In order to assess energy efficient building refurbishment process, DSSs should be capable of performing an accurate energy performance analysis on the whole building and its components and, based on that, analyze the most important retrofit measures. Once there are several retrofit measures, it should group them in a hierarchical way – from the more critical infrastructural to the less ones – in order to return different renovation scenarios along with their energy and environmental savings and a basic, yet strict, economic analysis. In addition, the DSS should be user friendly and adaptable for different stakeholders.

Considering that: i) a significant part of the European existing building stock is in great need of renovation, ii) the European established goals reinforce the need of retrofitting as a priority to mitigate climate change and improve energy efficiency, and iii) several research projects have shown that retrofit is the most cost-effective way to reach sustainability goals, this research focus on improving the decision making process for retrofit. It is thus fundamental to assess the importance of a DSS in the design retrofit phase and evaluate and compare the existing DSSs in order to suggest improvements to enhance the retrofit decision making process. Because the retrofit domain is evolving rapidly and most of the current DSSs for retrofit have been launched recently, the number of scientific studies concerning these DSSs is limited. The present study will contribute to enhance the research on decision support systems for retrofit by comparing the characteristics of existing tools.

This research project aligns with several projects developed by leading Institutions and their efforts to obtain solutions and achieve better understanding of how to assess the refurbishment process. Apart from private institutions in the USA, the two major institutions involved in developing these DSSs and projects are the International Energy Agency (IEA) and European Commission (EC) through specific programmes which aim to improve sustainability. The majority of their developed DSSs are free and public.

European efforts towards a sustainable building stock are still lacking of an accurate and efficient DSS to support decision making process. In order to try to fill this gap, this research will thereby focus on the need to unify DSS criteria within the EU. The renovation of the existing building stock and the reduction of the energy consumption are common goals in European countries. Therefore, understanding the common obstacles in the decision making process is relevant to develop an accurate European DSS. Standardization of methodologies to assess and evaluate energy efficient retrofitting should be a priority.

According to all the aforementioned, the research question of this thesis is the following:

"How can DSSs support energy efficient retrofitting measures in Europe?"

In order to answer this question the following sub-questions will be researched:

1) Which are the important energy efficient retrofit measures in a building?
2) How to evaluate the impact of retrofit measures on buildings?
    2.1) Decision support system selection
    2.2) Decision support system comparison

As a result of the answer given to the abovementioned research questions, the final chapter of this thesis gives recommendations to improve the existing DSS and/or to create a new DSS to achieve standardized criteria within the European Union.

1.4 Methodology

In order to answer the first sub-question an in-depth literature review was done. The intention was to identify the important energy efficient retrofit measures, based on the state-of-the-art of buildings refurbishment.

The methodology used to answer the second sub-question covered two parts: the selection and the comparison of the DSSs. For the selection of the DSSs for this study, a set of key performance indicators (KPIs) was developed based on the present research specific aims in addition to a literature review. The developed KPIs were used to select five suitable DSSs for this study through a multiple criteria decision analysis (MCDA). Establishing a decision matrix enabled several qualitative and quantitative factors to be taken into account in the decision process of selecting the DSSs to study.

The comparative research encompassed two aspects: the first compared general characteristics among the DSSs and the second compared the interface with the user.

For the comparison of characteristics, a list of indicators was developed based on an extensive literature research which identified the essential indicators to support and enhance the retrofit decision making process. The DSSs were then tested and their features compared against the list of indicators suggested. Finally, the DSSs were scored by the number of indicators presented and conclusions on their capabilities were drawn. The goal was to search for similarity in the DSSs in order to verify whether a "common language" was already being used and if not, to get insights regarding which aspects were missing to achieve a standardization of the retrofit decision making process.

The comparison of the interface of the DSSs was made using an adapted version of the model used by Staats (2013) to analyse the homeowner adoption of DSSs in the Netherlands. The model was adapted to the framework of the present research and applied to the five DSSs. The adoption attributes were analysed for each DSS and a multi criteria decision analysis was applied which enabled the evaluation of the user-friendliness of the DSSs.

The outcomes from the two comparisons of the DSSs were then discussed together and summarized and suggestions for an improved DSS were given.

1.5 Structure of the thesis

The present thesis is structured in seven chapters and four appendices, the content of which is further summarized. A diagram of the structure of the thesis is shown in Figure 2.

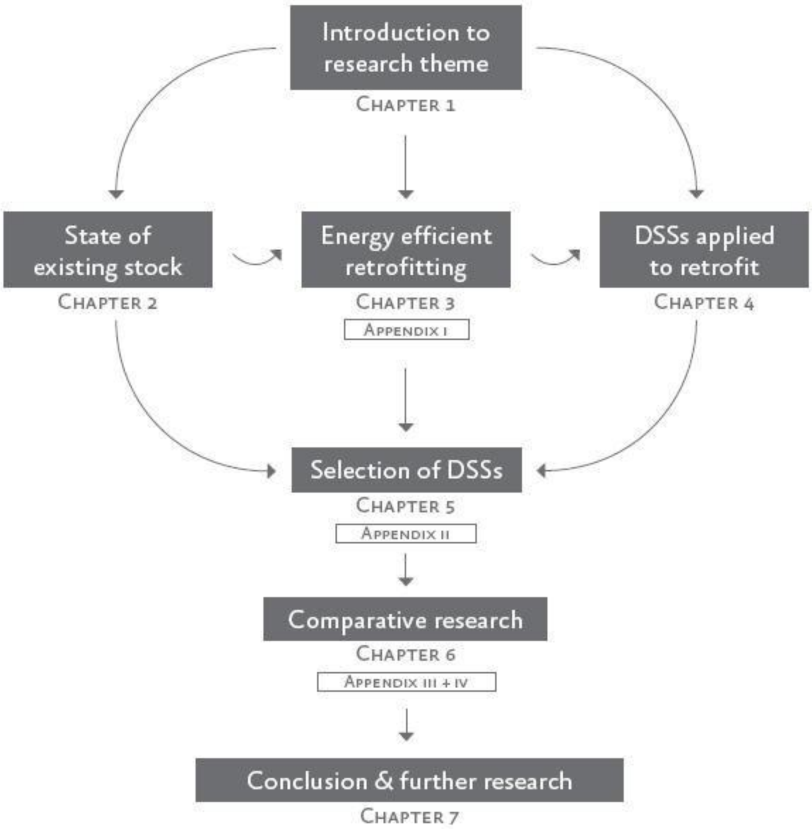

Figure 2 - Flow diagram of the thesis.

The present chapter, chapter 1, introduces the research theme and presents the fundamental goals for this research. The structure of the present study, the motivation of the research and its original contribution to the field of study is formulated in this chapter.

Chapter 2 makes the introduction of the European building stock with its general characteristics and detailed energy consumption. The importance of energy labelling in the building domain is discussed and retrofitting is argued as being a necessity and a mean to achieve energy efficiency in the building stock instead of other approaches.

Chapter 3 presents and describes the concept of energy efficient retrofitting.

Chapter 4 acknowledges decision support systems as a fundamental tool to aid the decision making process in the design of the energy efficient retrofitting process and its future potential.

Chapter 5 presents the selection of the DSSs for the comparative research.

Chapter 6 presents the comparison of general dimensions of the DSSs and the comparison of their interface with the user. The results are presented and discussed and advice on improvements in the DSSs is suggested.

In Chapter 7 the conclusions of the present research are presented and summarized, its limitations are discussed and advice for future research is suggested.

Appendix I presents the collected data from the literature review on the terms used to express energy efficient retrofit.

Appendix II presents the list of the DSSs found during this research that are designed to analyse specific retrofit measures in buildings.

Appendix III presents the original table of weights, parameters and benchmarks for each innovation characteristic as presented by Staats (2013).

Appendix IV presents the figures that illustrate the different innovation characteristics amongst the DSSs.

2. The state of the European existing building stock

The present chapter characterizes the state of the European building sector. In Section 2.1, the quantity of existing buildings in Europe and their variation according to typology, age, size and location are described. Section 2.2 discusses the energy consumption of the sector in detail and Section 2.3 discusses the importance of building energy regulation. Finally, Section 2.4 argues the urgent need of retrofit of the European building stock and discusses its potential.

2.1 Characterization

Europe has a rich, complex and extremely varied building stock. Different climatic zones, cultures, landscapes and an old history have all contributed to a large extent to a vast and diversified building stock such as the European. When compared with China and United States, Europe has the highest building density. Wealth conditions, culture and land availability make the floor space per capita much higher in Europe than in other regions of the world. This fact is in part explained by the increasing wealth conditions throughout Europe over the decades which led to the increasing demand for larger floor spaces[2]. The number of households in EU-27 increased by almost 10% in the period 2005-2013, reaching 212 million households in 2013 (Eurostat, 2014). At the present time, the European building stock represents 24 billion m^2 of useful floor area, with approximately 50% of that stock concentrated in urban areas as well as the majority of the population.

Buildings vary tremendously in relation with several factors such as typology, age, size and location. These factors altogether have a great impact on the thermal qualities of the building stock and therefore on the energy performance of the building stock. Hence it is of major relevance to understand and analyse the characteristics and conditions of the European building stock in order to define an efficient and effective retrofit intervention path. Improving the energy efficiency of the buildings not only reduces energy consumption but also improves the aesthetics of the building, increases the value of the asset and provides healthier conditions for the occupants (BPIE, 2011).

Within the sector, residential buildings represent 75% of the total floor area (m^2), while the remaining 25% of the buildings are non-residential (services) as Figure 3 shows.

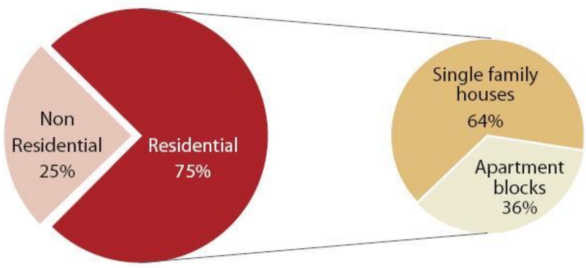

Figure 3 - Building floor space by type in the EU-27 in 2009 (BPIE, 2011).

Whereas residential building stock can be divided into single family houses (64%) and apartment blocks (36%), the non-residential building stock is more complex and heterogeneous, encompassing types of buildings that are very diverse. The majority of the non-residential building stock is covered by wholesale & retail (28%) and offices (23%), followed by educational buildings (17%), hotels and restaurants (11%), hospitals (7%), sports facilities (4%) and other types of buildings (11%) (Figure 4). The variety and complexity of this sub-sector of buildings is intensified by the variations in size, usage

[2] The average size of dwellings in Europe is around 99 m^2.

pattern, energy intensity and construction techniques (BPIE, 2011). On the other hand, residential buildings are more homogeneous in the same characteristics since they all serve the same function. Furthermore, they constitute the majority of the building stock and are therefore the focus of the present research.

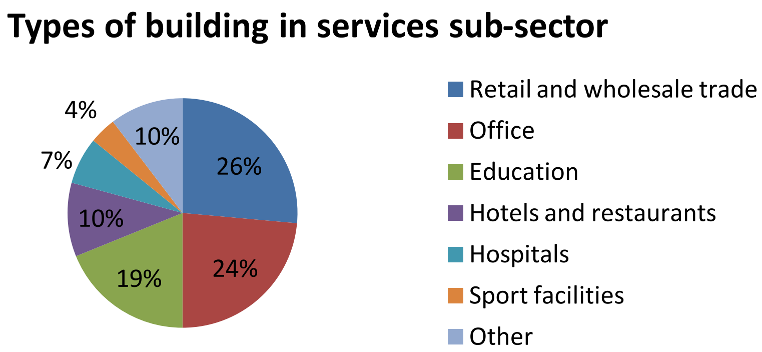

Figure 4 - Typologies in the non-residential building sector (BPIE, 2011).

Due to a rich, complex and heterogeneous history, buildings throughout Europe present several different construction periods which vary from country to country, with many buildings accounting for more than a century. According to a survey conducted by BPIE (2011), which classified European buildings in age bands, the biggest percentage of residential buildings are “modern”, constructed between 1961 and 1990, followed by “old” buildings (previous to 1960) and “recent” buildings (between 1991 and 2010). During the “modern” period (1961-1990) a construction boom occurred across all countries and the housing stock increased more than twice. Although the share of “old” buildings is relatively large in every region, only in the North & West region[3] it represents the major fraction (42%). On the Central & East[4] and South[5] regions, “modern” buildings constitute almost 50% of the total housing stock and recent buildings less than 20%.

The ownership of buildings and the question of tenure influence the willingness to take action on retrofit actions to improve the energy performance of buildings and therefore, the rate at which buildings are retrofitted. Throughout Europe, the largest majority of residential buildings are held in private ownership, while 20% in public ownership and at least 50% of these buildings are owner-occupied while the others are rented from private and public landlords. Multiple owners and/or occupants of buildings tend to make difficult the agreement on energy savings investments, being multi-stakeholder issue a barrier to retrofit interventions. The European building stock is wide and its characteristics depend of several factors. Yet, in such a diverse building environment, it is possible to identify typologies which can help us defining a path towards a complete renovation of the building stock. In the next section the energy consumption of the residential sector is discussed in detail which unveils the priority retrofit intervention areas in the sector.

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[3] North & West region covers Austria, Belgium, Switzerland, Germany, Denmark, Finland, France, Ireland, Luxembourg, Netherlands, Norway, Sweden and United Kingdom.

[4] Central & East region covers Bulgaria, Czech Republic, Estonia, Hungary, Latvia, Lithuania, Poland, Romania, Slovenia and Slovakia.

[5] South region covers Cyprus, Greece, Spain, Italy, Malta and Portugal.

2.2 Energy consumption

According to Eurostat (2012b), the final energy consumption[6] in the European Union in 2010 was 1153 million tonnes of oil equivalent (13409 TWh), with Germany, France, Italy, United Kingdom and Spain being the major consumers[7]. Within the 27 members, transport accounts for 31.7% followed by households with 26.7%, industry (25.7%), services (13.2%), agriculture (2.2%) and other consumption (0.9%). Nevertheless, when adding residential sub-sector (households) with non-residential (services), the building sector alone accounts for approximately 40% of the total final energy consumption in Europe (5364 TWh). It is then, by far, the largest energy consumer sector, which makes of it an attractive opportunity to largely reduce energy consumption in Europe.

Within the building sector, residential buildings represent approximately 65% of the final energy consumption of the sector. Nevertheless, the fact that residential buildings represent the biggest share of final energy consumption does not mean that they consume more. In fact, non-residential buildings present a higher growth rate during the period of 1990 to 2009 (1.5%/a) than residential buildings (0.6%/a) and also a higher energy use per m^2 (295 kWh/m^2) when compared to residential buildings (200 kWh/m^2). This highest consumption is explained by two main reasons: i) the purpose of non-residential buildings is different which makes the use of electrical appliances and air-conditioning more common and intensive, and ii) the economic and population growth in developed countries is reflected on the shift on the economic structure from industries to services.

During the year of 2010 the residential sector alone consumed 3574 TWh, the highest level of the last 20 years. In these last two decades, residential consumption grew by 12.4%, reaching a first peak in 2005, decreasing in the forthcoming years and again reaching a peak in 2010. It is a fact that energy consumption trends are strongly influenced by factors such as economic development, population growth and weather conditions, and events like 2007 (lower heating degree days [HDD]) and 2010 (winter unusually cold; economic rebound effect) are a reflection of that influence. However, the overall trend observed is that energy consumption in the residential sector started to decrease in the last years (Bertoldi, Hirl, & Labanca, 2012). Energy efficiency efforts may have contributed to a large extent to this trend. According to Lapillone and Pollier (2014), the residential sector has achieved the largest energy efficiency improvement with a regular energy efficiency gain of 1.6% per year since 1990.

The average energy consumption per household in the residential sector is 16.3 MWh annually or roughly 7 MWh per capita (Lapillonne, Sebi, Pollier, & Mairet, 2012). As Figure 5 shows, the major energy consumer is space heating (64.7%) and the second largest consumer is water heating (14%) followed by electrical appliances (12%), cooking (6%), lighting (3%), and finally, with a marginal share of the energy consumption, space cooling (0.3%).

[6] Final energy consumption refers to the energy effectively used in the daily operation of buildings, after its conversion and transformation process from primary energy.

[7] These five European countries together represent approximately 65% of the total floor area of the building stock.

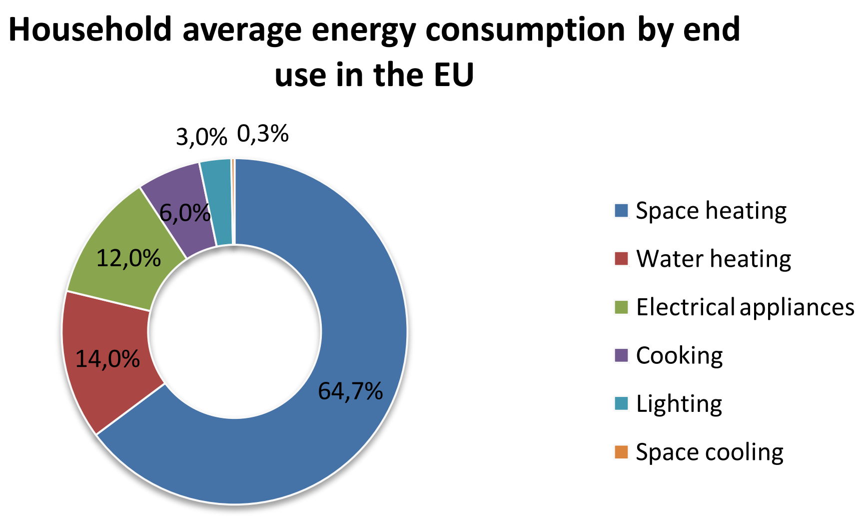

Figure 5 - Average final energy consumption by end use in the residential sector of the EU-27 in 2011 (Lapillone & Pollier, 2014).

Space heating is the major energy consumer in a building due to the cold winters (high level of energy required) combined with the low levels of insulation of the building envelope that cause massive heat losses. There is a correlation between HDD and fuel consumption which means that during years with colder winters (more HDD), the fuel consumption directly increases. It reflects a clear link between climatic conditions and energy use for heating and it is therefore common the existence of year-to-year fluctuations in space heating consumption. Although with those fluctuations observed, the share of energy consumption for space heating is slightly declining since 2000 due to energy efficiency regulations and the diffusion of more efficient heating technologies. The Netherlands can be regarded as a benchmark for space heating as it presents the lowest specific energy use per m^2 and per HDD (Lapillonne et al., 2012). Lighting consumption is also declining due to the effect of energy efficiency regulations. The energy consumption for water heating and cooking remains stable. The strong increase since 2000 is observed in electrical appliances.

Natural gas is the dominant source of energy for households in European countries, followed by electricity, oil, renewable energies, heat[8] and solid fuels. Figure 6 shows the percentages of each energy source for EU-27 in 2011.

[8] Heat is the by-product of electricity production in power stations. A *combined heat and power* (CHP) plant takes advantage of both electricity and heat produced. The heat is then delivered in the form of hot water or steam through a heat distribution network known by the name of *district heating*.

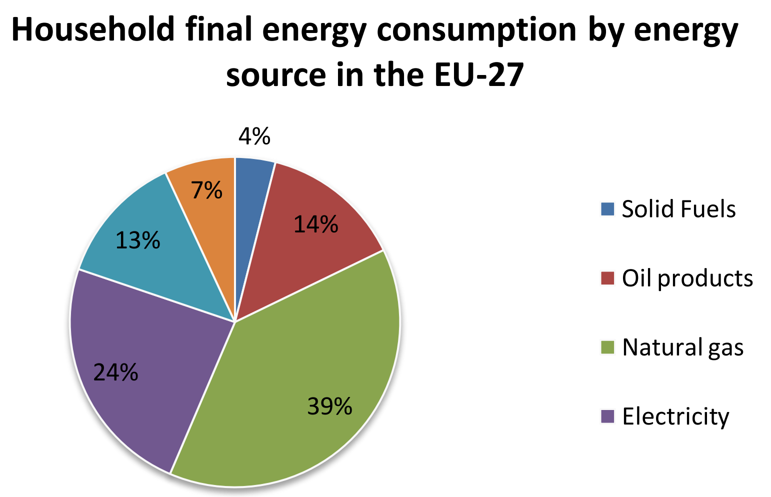

Figure 6 - Final energy consumption by energy source in the residential sector for the EU-27 in 2010 (Eurostat, 2012b).

Within the solid fuels, coal is still being used in Central & East Europe, being Poland its largest consumer. Although oil use fell by 24% since 2000, it still represents a bigger fraction of energy use in Europe, with France and Germany dividing the highest shares. Heat delivered through district heating is more common in Central & East Europe and its share in the final energy consumption remains more or less constant. Whereas solid fuels, oil and heat consumption decreased since 2000, the consumption of all other energy sources increased. The highest increase was in renewable energies (37%), followed by electricity (18%), solid fuels (10%) and natural gas (6%) (Eurostat, 2012b).

Analysing the values over the period 1990-2010 unveils a clearer shift in the mix of fuels used in the building sector. On the one hand, electricity and gas use increased 50% and on the other, the use of oil decreased by 27% and the use of solid fuels by 75%. Oil and solid fuels (e.g. wood) are being phased-out and their decrease is mostly due to the shift to gas use and the increasing wealth conditions. Nevertheless, the use of oil still remains significant in island countries. Regarding electricity use, its increase is explained due to the generalization of a diverse range of household electric appliances and equipment which is associated with a higher degree of basic comfort and level of amenities. The general trend in the residential sector has been an increase in electricity consumption. For example, during the period 1990-2010, the final electricity consumption for the residential sector has grown by 38.7%, from 604 TWh to 843 TWh (Eurostat, 2012a). However there are differences between the trends of different electricity end uses. For instance, the consumption of lighting is decreasing due to the phase-out of incandescent lights whereas the consumption of information and communication technologies (ICT) and consumer electronics (CE) is still rising (Bertoldi et al., 2012). Although the residential electricity consumption per capita is still increasing (1682 kWh in 2010), the average growth rate is decreasing since 2005. Thus, it can be expected that residential electricity consumption will finally start to decrease in the near future (Bertoldi et al., 2012).

Another relevant analysis is of the CO_2 emissions of the residential building sector. Between 1997 and 2007 the CO_2 emissions declined by 24% (or 91 Mt), from 499 to 413 Mt of CO_2e ("Energy efficiency", 2011). In the same period the household stock increased and the number of appliances used also increased. Thus, an increase in CO_2 (99 Mt of CO_2e) emissions, as well as in the energy consumption, was to be expected. The reduction in the level of emissions was a result of energy efficiency improvements and the already mentioned shift in the mix of energy sources used in the sector. The switch to energy sources with a lower CO_2 content made possible to achieve this large reduction in the building sector.

According to the analysis of the electricity consumption breakdown provided by the Join Research Centre (Bertoldi et al., 2012), the largest electricity consumers in European households in 2009 were electric heating systems (19.1%), cold appliances (14.5%), lighting (10%) and water heating systems

(8.8%). Entertainment consumes 8.3% and office equipment 7.2%, which together occupy the third place in the largest energy consumers with a share of 15.5%. Washing & drying consumes 7.2% followed by electric ovens, grills & hobs (6.6%), ventilation and air conditioning (4.7%), vacuum cleaners (3%), dishwashers (3%), set-top boxes (1.7%) and other (5.9%). Because of the fast and widespread use of ICT and CE, standby energy consumption is another fast growing end use, one that offers a considerable saving potential. In 2007, home appliances standby consumption accounted for 5.9% of the global residential electricity consumption (Bertoldi, & Atanasiu, 2009).

As discussed before, energy efficiency programmes were effective in reducing energy consumption and raising awareness in the consumers for the last decade. The decreasing trend of energy consumption in the sector clearly demonstrates that. Nevertheless, the energy consumption of the residential building stock is still at a level that is impossible to maintain if the goals of avoiding climate change are to achieve in the near future. The next section introduces the European regulations on buildings and discusses its importance and role in the regulation of the building energy consumption.

2.3 Building energy regulation

Besides setting goals for energy efficiency in buildings to achieve in a near future and defining which measures should be applied to effectively reach the goals, it is necessary to understand how to implement a strategy to effectively reduce the energy consumption. In such a diverse and complex building environment it is necessary to encourage stakeholders to be an active part of the sustainable building process. Energy policy in buildings can be viewed as a tool to make this process faster and contribute to standardize the solutions. By the means of regulation, auditing and certification, the three instruments available to regulatory bodies, energy efficiency in buildings can be promoted and encouraged (Pérez-Lombard, Ortiz, González, & Maestre, 2009). Building energy regulations are needed to ensure energy is used in an efficient way and that final energy consumption is reduced without compromising comfort or productivity levels. The strategy is to establish minimum requirements for energy use in buildings. On the other hand, building energy labelling informs stakeholders about energy performance of their buildings and allows straight comparison between different buildings, while promotes energy savings and energy efficiency at the same time.

Reducing energy consumption in the residential and tertiary sector is simultaneously a need and a priority acknowledged by the European Union, encompassing multiple achievements: i) the compliance with international agreements (e.g. Kyoto protocol), ii) the reduction of the energy dependency, iii) the reduction of the CO_2 emissions and iv) an opportunity to lead the development path towards sustainability. It is in this context that, since the 1970's, the European Union has developed several regulatory instruments to tackle energy efficiency in buildings, by introducing regulations on the building envelope, building design, building thermal services and domestic appliances. However, only in 2002 a regulatory instrument specifically focused on the energy performance of buildings has been introduced (Directive 2002/91/EC). This new Directive intended to achieve the great unrealised potential for energy savings in buildings and to reduce the large differences of the energy performance of the building stock between the Member States. The Energy Performance of Buildings Directive (EPBD) introduced the following key requirements for Member States:

i) Minimum requirements on the energy performance of new buildings and existing buildings undergoing "major renovation";

ii) Methodology for calculating the integrated energy performance of buildings;

iii) Energy certification for both new and existing buildings whenever they are constructed, sold or rented out;

iv) Regular inspection of heating and air conditioning systems;

The mandatory energy certificate for new and retrofitted buildings should contain a numeric indicator of the energy performance of the building, the label associated and some recommendations to improve the energy efficiency.

However, the 2002/91/EC Directive lacked sufficient detail for a clear and consistent implementation across the EU members (Pérez-Lombard et al., 2009) and, in 2010, the Directive was recast with substantive amendments and new requirements. In general, the recast was a strengthening of the energy performance requirements of new as well as existing buildings across EU, setting ambitious goals to achieve in the near future. For new buildings, the recast fixed 2020 as the deadline for all new buildings to be nearly zero-energy buildings[9] (NZEB). Although no specific targets have been set for existing buildings, Member States were required to develop policies and set targets to increase the number of NZEBs that result from retrofitting. Furthermore, the recast extended the scope to almost all existing buildings by eliminating the 1000 m^2 threshold for major renovations, which formerly excluded 72% of the building stock (BPIE, 2011). Existing buildings undergoing a "major renovation" are now forced to meet the minimum energy performance requirements. The changes introduced with the recast concerning the existing building stock represent a large encouragement and incentive to highly energy efficient retrofitting and may influence the extension and rate of renovation of the building stock. In addition, energy certification provides information that may increase the demand for more efficient buildings, thus contributing to improve the energy performance of the building stock in each country. If prospective purchasers and tenants come to regard an energy certificate as important to their decision making, building owners will have greater incentive to improve the energy efficiency of buildings (IEA, 2010).

Energy certification is a significant tool for improving the overall efficiency of the entire building stock. The estimated impact with the implementation of the recast Directive is to reduce the European building energy consumption by 5-6% by 2020, the equivalent to 60-80 Mtoe (European Commission, 2008). However, as buildings have long life spans, the turnover is low, and it will take a long time before new building codes, policies and certification schemes for new buildings have any significant impact on the building stock as a whole (IEA, 2010). This fact reinforces that the great potential for energy savings lies in the existing buildings.

Although the majority of European countries did not have any regulation on the energy performance of buildings until the EPBD, some countries had already developed and implemented important regulations. Switzerland developed the MINERGIE building standard in 1998. Unlike the mandatory nature of the European certification scheme, MINERGIE is a voluntary building standard, developed by a non-profit association and supported by the Government. In 2009 Switzerland had already 14000 buildings voluntarily certified (Beyeler, Beglinger, & Roder, 2009). A MINERGIE building consumes approximately 60% less energy than a conventional Swiss building. The standard applies for new and retrofitted buildings and focuses on an integrated planning approach and life cycle costs. Like EPBD, the MINERGIE label has minimum requirements on the specific energy consumption of the building.

Another ambitious certification scheme is the Passive House standard, representing the highest energy standard today. The Passive House concept has been developed since the 1970's together with the concepts of super insulation and passive solar techniques. The concept was then refined and fully developed in Germany during the 1990's. Like the MINERGIE label, Passive House standard is also voluntary and international. According to the International Passive House Association (IPHA, 2014), in 2013 more than 50000 buildings have already been built worldwide according to the Passive House standard. The basic idea of the concept is to improve the thermal performance of the envelope to a level that the heating system can be kept very simple (Feist, Schnieders, Dorer & Haas, 2005). Besides criteria on space cooling, primary energy, air tightness and thermal comfort, the requirement for space heating demand of new buildings states that it shall not exceed 15 $kWh/m^2.yr$. The challenging

[9] A NZEB is defined as a building that has a very high energy performance requiring nearly zero or a very low amount of energy which is mostly supplied with energy from renewable sources produced on-site or nearby (European Parliament and the Council of the European Union, 2010).

conditions of existing buildings due to intrinsic aspects that are impossible to correct, make Passive House standard for retrofits prohibitive. In order to fill this gap, a label especially designed for retrofits was developed in 2010. The standard respects the Passive House principles but is based on different criteria. For instance, the space heating demand of retrofitted buildings shall not exceed 25 $kWh/m^2.yr$.

Energy certification of buildings is a key policy instrument for reducing the energy consumption and improving the energy performance of new and existing buildings. The large energy savings already achieved in buildings would not have been possible without building regulations. However, it is still a long road to a sustainable building stock. The great unrealized potential lies in strengthen and deepen the European efforts, achieve standardized solutions and focus on improving the existing building stock. Section 2.4 discusses the relevance of retrofitting in achieving the large potential that hides in the existing European building stock.

2.4 The necessity and the potential of retrofitting

It is clear the building sector is the priority to achieve large savings once it is the largest consumer. For an opportune reduction in global energy consumption and an effective improvement of environmental sustainability, a rapid enhancement of energy efficiency in existing buildings is required (Ma et al., 2012). The EPBD is a relevant instrument for reducing energy consumption and GHG emissions. Still, the estimated impacts on energy savings are far from what is needed in order to realise the ambitious targets for improving energy efficiency by 2020 and the even more ambitious targets for GHG emissions reductions by 2050. Two important aspects of the EPBD hinder the potential for larger energy savings. On the one hand the effect of new building standards is restricted by the limited volume of construction. In the EU the new building construction rate is roughly 1% a year (Power, 2008; Lapillone et al., 2012). On the other hand, according to BPIE (2011), the renovation rate across Europe is also 1%. EPBD requirements for retrofitting existing buildings are weakened once there are no effective instruments to drive the market to increase the rate of renovation. New policies and better implementation of the existing policies in order to encourage and incentive stakeholders are of paramount importance if the goals of energy reduction are to be met. Furthermore, it is necessary a long term vision for the retrofit of the building stock to very high energy performance levels by the middle of the century.

The most effective way of achieving the energy and CO_2 targets in buildings is through the reduction of the energy demand and the use of clean energy sources with low or zero carbon content. Besides, retrofit is an opportunity to reduce the energy dependence, and therefore improve the security of the energy supply, and lead the path towards sustainability. The impacts of undertaking energy efficient retrofitting of buildings are wide and vast. In the social sphere it is an opportunity to end with fuel poverty, improve health living conditions and increase comfort and productivity. The environmental benefits of retrofit are not only reducing CO_2 emissions but also air pollution (e.g. SO_2, NO_x) due to decreased use of fossil fuels, therefore contributing to a large extent to avoid climate change. Regarding energy impacts, it would contribute to improve energy security, avoid new generation capacity and reduce the peak loads. Retrofit buildings to a high energy performance would stimulate economy by creating a large number of jobs and increasing the disposable income of the families. In addition, it would increase the EU gross domestic product, have a positive impact on public finances, and increase the value of the properties and the research & development. The list of benefits is extensive. As BPIE (2013) summarizes, renovating the buildings of a nation improves the health and the wealth of its citizens.

Retrofit is also a more desirable option than demolition. Demolition as a tool for urban renewal and improvement of living conditions may seem easier and quicker to reduce energy use. However, as argued by Power (2008), the building construction process and the materials used are highly energy intensive and constructing new dwellings would consume four to eight times more resources than an equivalent retrofitting. This is mostly due to the fact that the structural elements in an existing building only rarely need replacing. Therefore, a retrofit avoids the requirement for new materials and has smaller environmental impacts. As good as the long run energy efficiency of the new building might be, it is outweighed by the energy its construction would require. Demolition is a slow, costly and unpopular process and it should therefore be taken as a last resort.

Buildings have a long structural life, often exceeding 60 years (Konstantinou, & Knaack, 2013). However, building envelope shows signs of obsolescence only after 20 or 30 years. Taking into account that more than 40% of European building stock was constructed before 1960 and that thermal insulation standards were only introduced in the 1970's after the energy crisis, it is with no surprise that the older building stock present the worst energy performance. The performance of the space heating system and the quality of the building envelope are directly related to the year of construction and its techniques. The low insulation levels, the high air tightness levels and the inefficient systems in buildings constructed before the 1960's reflect the practically inexistent requirements for energy efficiency. This share of the building stock tends to present unhealthy living conditions, to consume more energy and thus, contributes to a large extent to the high energy consumption of the sector. The oldest part of the building stock is in great need of retrofitting and holds a great potential for energy savings and for the improvement of living conditions of the occupants. It should therefore be the priority for renovation policies.

From 2030 onwards the emphasis should be shifted to the modern age share of buildings, which derived from the construction boom between 1961 and 1990. The share of buildings constructed in the current decade would not need to undergo renovation until 2040 (BPIE, 2011). In order to substantially renovate the national building stocks with the strategy aforementioned it would take approximately 30 to 40 years, which means a retrofit rate of 2.5-3% a year. On the other hand, also the scale of the retrofits has to increase. It is estimated that most of the present retrofits achieve only modest energy savings (20-30%), thus not realising the total economic and energy potential. The depth of the retrofits needs to shift to be above 60% of energy savings in the period 2020-2050. As modelled by BPIE in its publication "Europe's buildings under the microscope" (2011), only in the scenario where the rate and depth of renovation are substantially increased and the energy supply system is rapidly decarbonised, could the 2050 targets be achieved. In this study, BPIE has developed a number of possible scenarios for the renovation of the EU building stock by 2050. Assuming the "baseline scenario", in which the current retrofit depth and rate prevail, only 40% of the building stock is renovated by 2050 and only a 9% reduction in energy consumption is achieved. Under this scenario also the economic impacts are hindered: less than 200 000 jobs would be created until 2050. On the contrary, the "deep scenario", which combines a deep renovation path with a medium rate of retrofit growth, would deliver high energy (68%) and CO_2 (70-90%) savings and would have the highest employment effects by 2050 (1.1 million direct jobs for the next 40 years). The investment costs would be the highest of all scenarios, amounting to 937 billion € but so would the energy savings, estimated in 1318 billion €. The analysis provided by BPIE (2011) shows that the retrofit investment is cost-effective and that only with a high investment and a dynamic retrofit market would be possible to achieve the settled targets and goals for both 2020 and 2050. The analysis of the scenarios clarifies and reinforces the economic, social, energy and environmental benefits of retrofitting the building stock.

2.5 Summary and conclusions

The present chapter started with the characterization of the wide and vast European building stock and discussed the energy consumption of the residential sector. After a discussion of the importance of building energy regulations in the improvement of the energy performance of the building stock, it finished with the discussion of the urgency of a complete renovation of the building stock and the potential benefits.

Due to a complex and rich past the existing building stock present many typologies, that vary according to characteristics such as age, location, size and construction techniques. The present research is focused on residential buildings, which represent 75% of the existing stock and has more homogeneous characteristics (e.g. size, usage pattern, energy intensity). More than 40% of those buildings were constructed before 1960 and, due to the absence of building regulations at the time of construction, is the share of the stock that has the worst energy performance levels.

The energy consumption of the residential buildings is 27% of the total European consumption and therefore represents a unique opportunity to achieve considerable energy and GHG emissions savings. Within the residential sector, space heating is the largest consumer and natural gas the dominant source of energy. Therefore, the strategy to improve the energy performance of the dwellings should focus on reducing the energy demand and decarbonising the energy supply. For instance, the reduction in CO_2 emissions observed in the last years (1997-2009) is a reflection that variations in the energy supply mix highly influence the CO_2 performance of buildings. Although a strong growth in electricity consumption driven by an increase in the ownership and use of electrical appliances has been observed, the general trend in the residential sector has been a decrease in the energy consumption. This is mostly due to the introduction of energy efficiency regulations and the increasing awareness of different stakeholders. The EPBD is a key policy instrument for reducing the energy consumption and improving the energy performance of new and existing buildings. Nevertheless, its effects are hindered by a decreasing rate of new building construction and by an absence of tools to improve the market to increase the rate of renovations.

The energy performance of the European building stock should be significantly improved in order to achieve the ambitious targets for improving energy efficiency by 2020 and the even more ambitious targets for GHG emissions reductions by 2050. In order to have the European building stock renovated until 2050, an average renovation rate of 2.5% a year needs to be attained. With current rates as low as 1%, the levels of activity need to more than double to achieve the total renovation of the building stock. For this to be a reality new policies and better implementation of the existing ones is needed in order to encourage and incentive stakeholders. A complete renovation of the building stock would have larger impacts in stimulating the economy, achieving enormous energy and GHG emissions savings, increase the security of the energy supply, reduce the European energy dependency and increase health and living conditions. More than anything, it would represent a large step to avoid climate change and a remarkable opportunity for Europe to lead the path to a sustainable future. The next chapter presents and discusses the concept of energy efficient retrofitting.

3. Energy efficient retrofitting

The words refurbishment, retrofitting and renovation have been interchangeably used in this research to express the works needed to upgrade the energy efficiency and environmental performance of an aged or deteriorated building. In section 3.1 the meaning of these terms and the way in which they are employed in the literature is reviewed and the concept of energy efficient refurbishment is defined. The key phases that constitute the refurbishment process are described in section 3.2, and an overview of the retrofit measures that should be considered in building refurbishment is given in section 3.3.

3.1 Terminology and concept

Many words are used in the literature to refer to the works needed to upgrade the energy and environmental performance of a building. Nonetheless, few are the authors that give clear definitions of the expressions used to describe this type of works. Instead, they keep the meaning implicit in the text. Having a large variety of partly overlapping terms in use can result in a general lack of accuracy and contribute to generate misleading interpretations. Amid the common terms used in the literature are: refurbishment, retrofitting, renovation, renewal, reconstruction, restoration, repair, adaptation, upgrading, modernization and transformation. Power (2008) makes equivalent use of the expressions refurbishment, renovation, renewal and repair to refer to building energy efficient upgrade when contrasting it against building demolition. Thuvander, Femenías, Mjörnell, & Meiling (2012), justify the use of such a diverse terminology with the varied type and scale of buildings, the large range of actions undertaken and the variety of reasons and motivations for making an intervention. In fact, the works to improve the energy efficiency of a building can range from minor repairs in the building envelope to major renovations with significant alterations to the original state of the building (e.g. in the façade of the building).

However, after an in depth literature review [10], the most frequent terms to refer to the work required to upgrade the energy and environmental performance of an aged or deteriorated building are retrofitting, refurbishment and renovation. Some authors (Kolokotsa Diakaki, Grigoroudis, Stavrakakis, & Kalaitzakis, 2009; Flourentzou & Roulet, 2002; Alanne, 2004) present a distinction between the two terms. Alanne argues that the concept of “renovation” is usually divided under two categories: retrofit and refurbishment. They define refurbishment as the necessary modifications in order to return a building to its original state, while define retrofit as the necessary actions to upgrade it to new requirements or more specifically, that will improve the energy and/or environmental performance of the building. These meanings seem to be in accordance with the entries of refurbishment[11] (2013) and retrofitting[12] (2013) found on the Cambridge Dictionary. Nevertheless, different authors define refurbishment as the works involving improvement, adaptation, upgrading, renovation, rehabilitation, modernization, conversion, retrofit, and repair of existing buildings (Juan, Kim, Roper, & Castro-Lacouture, 2009; Egbu, 2010). Even with the most frequent terms, a lack of coherence and agreement on the meaning of those terms is observed.

There are other authors that use these terms interchangeably and, in order to be more specific on the extension of the works, create distinctions based on energy and economic criteria (i.e. energy savings, money savings). The term retrofitting is often divided into “conventional” and “deep energy” (Rysanek & Choudhary, 2013; Zhai, LeClaire, & Bendewald, 2011). A deep-energy retrofit is the process that yields buildings that save at least 50% annual energy costs with an attractive net present

[10] A summary of the data collected is presented in Appendix I;

[11] Refurbishment: “to make a building look new and bright again”;

[12] Retrofitting: “the act of providing a machine with a part, or a place with equipment, that the machine or place did not have when it was built”;

value (NPV) while a conventional retrofit will achieve 15-25% energy savings and attractive financial returns (Zhai et al., 2011). Furthermore, the deep-energy retrofit is defined as a large-scale intervention that significantly alters the architectural design and the building components and operations, while the conventional retrofit is of smaller scale, intervening just in some building components and/or in replacing one or more building technologies (Rysanek & Choudhary, 2013). Hermelink and Müller (2011) make the distinction based on the definition of “major renovation” given in the European Directive on the Energy Performance of Buildings (Directive 2010/31/EU), which refers to a renovation with total costs higher than 25% of the value of the building or in which more than 25% of the surface of the building envelope undergoes renovation (EPCEU, 2010).

Considering the common and comprehensive use of the words renovation, retrofitting and refurbishment in the literature and the distinction between them, argued by Kolokotsa et al. (2009) and Flourentzou et al. (2002), the term retrofitting was adopted in the present research. Thus, to be able to distinguish the scale of the intervention works, “deep-energy” and “conventional” definitions, provided by Zhai et al. (2011), were adopted.

As discussed in Section 2.4 the need to retrofit the European existing building stock is essential to achieve the ambitious goals of energy efficient buildings and sustainable cities. With the overall target to minimize the global impact of the built environment in the short and long term, sustainable retrofitting will contribute to a significant extent to transform the cities we live into sustainable cities. Through the combination of the efficient use of resources with the satisfaction of the social, environmental and economic needs in a long-term perspective one will make the process of building refurbishment sustainable. Mickaityté, Zavadskas, Kaklauskas, and Tupėnaitė (2008) argue that sustainable refurbishment consists in the comprehensive integration of technical-ecological aspects of building life cycle and the satisfaction of social and economic needs. The authors present five principles to establish a sustainable refurbishment:

- **Citizen’s healthcare:** healthy living conditions must be ensured by improving the quality of indoor microclimate and external environment.
- **Effective energy use:** reduce energy demand by applying energy-efficient measures (improve building envelope and heating, ventilation and air-conditioning (HVAC) system).
- **Rational resources use:** encourage efficient construction materials and natural resources use, extend building life cycle and decrease the waste generated.
- **Environmental conservation (responsibility):** minimize building impact on the environment (e.g. ensure sustainable energy supply).
- **Affordability:** energy and environmental conservation and quality living conditions should be affordable to people.

These principles reflect not only the efficient use of resources but also the social, economic and environmental dimensions of sustainable refurbishment. In order to understand how to evaluate the impact of different retrofit measures in the built environment (see Section 1.3), these principles were considered on the retrofit scenario analysis performed by the decision support systems (see Chapter 6).

The focus of the present research is on DSSs applied to energy efficient retrofitting. This particular retrofitting is considered as a step towards a sustainable living environment. The substantial difference from a sustainable retrofitting consists in the fact that an energy efficient retrofitting focuses only on reducing the energy use of the building. This means that it does not consider the reduction of water use or materials use, except in cases in which it is directly connected to the reduction of energy use. The overall goal is to reduce the energy use of the building by improving its energy performance, reducing the carbon emissions of its operation and, as a result, extending the building life cycle. Therefore, the strategy is to minimize the energy demand through thermal improvement of building envelope, reduction of heat losses in heat distribution systems and sources and total or partial replacement of heat sources. On the other hand, it is necessary to ensure a sustainable energy supply by meeting the energy demand with renewable energy sources (RES), encouraging bioclimatic[13] building design and orientation and implementing energy storage.

Through the improvement of indoor thermal comfort of the building and its air quality, the reduction of its energy demand and its dependence on fossil fuels in a cost-effective manner is possible to satisfy the needs of the social, environmental and economical dimensions. By minimizing the global impact of the building stock in the environment in the short and long term, energy efficient retrofitting is a step towards sustainable buildings.

3.2 Key phases of a retrofit project

Although an energy efficient refurbishment is focused only on reducing the energy use, it is an interdisciplinary process subject to many constraints and limitations. The goal of the project and its targets together with the financial budget define the scope of the retrofit project which is then influenced by the building specific characteristics (e.g. location and orientation), the building energy performance (assessed through an energy audit) and the available technologies for the retrofit of the specific building. This process is illustrated in Figure 7. These factors altogether influence the type and extension of the project to implement, making of each refurbishment project a unique and complex optimisation problem.

However, in the phases it incorporates, the retrofit process is similar to a new construction process: it involves project definition, design, construction, commissioning and occupancy. The main difference consists in the project definition phase which requires a complete and comprehensive documentation of the existing building conditions. An energy audit is fundamental to: i) assess the current building energy performance, ii) understand the energy use of the building and iii) identify the areas with the largest potential for energy savings. At the same level, the assessment of the building specific characteristics enables the identification of the renovation needs of the building and determines the implementation of certain retrofit measures. Another factor that should be considered is the availability of technologies to retrofit. According to the current state of the building and taking into account that it is also limited by the goals, targets and financial budget, there is a range of suitable technologies that could be employed. Besides documenting the existing building conditions, the goals and targets settled by the building owner determine the type and extension of the project and the technologies to retrofit. In short, the five factors require to be evaluated together.

[13] Bioclimatic architecture refers to an alternative way of constructing buildings that take local climate conditions into account and optimize the use of renewable resources, by using passive technologies, in order to improve energy efficiency (Tzikopoulos, Karatze, & Paravantis, 2005).

Figure 7 - Factors affecting the scope of the retrofit project.

Once a decision is made, the scope of the retrofit project is defined and the extension and type of the retrofit project are determined. The subsequent phases to the setup phase are outlined in Figure 8. A profound analysis of the energy auditing is required to identify definitive cost-effective energy conservation measures (ECMs) and identify the definitive retrofit options to implement. This phase includes the use of energy models, economic analysis tools and risk assessment methods in order to assess the performance of the retrofit options in the building to retrofit. The quantitative assessment of money and energy savings enables to choose the suitable and cost-effective options. After the retrofit measures are selected, the next phase is to implement the retrofit project. The implementation of the measures should be complemented with test and commissioning to ensure the building and its services systems operate in an optimal manner. The last phase consists in verifying the energy savings achieved using measurement and verification methods. A post occupancy survey is also important to ensure the satisfaction of the occupants of the building with the retrofit project (Ma et al., 2012). Building energy management and control system (EMCS) may also be implemented in order to allow the monitoring and controlling of the operation of the building services systems and ensure that thermal comfort and energy efficiency is maintained.

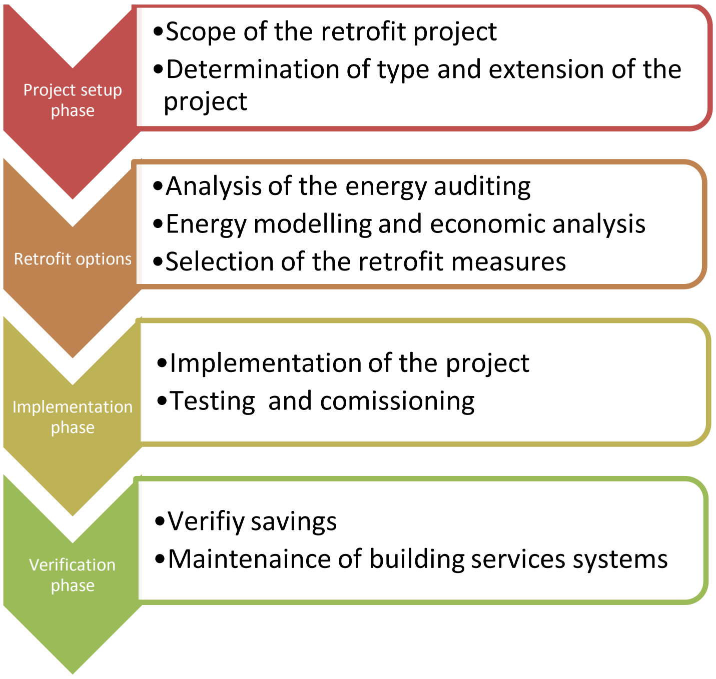

Figure 8 - Key phases of a retrofit project.

3.3 Retrofit Measures

In order to improve the energy performance of a building, any retrofit intervention should address some fundamental aspects concerning energy use in the operation of a building. To understand the energy improvements due to retrofitting, this research uses the approach of the *Trias Energica*, developed by Lysen (1996). Applied to the buildings sector, this approach involves achieving energy efficiency, the use of renewable energy sources and the clean use of fossil fuels. Thus, the strategy proposed in this research to reduce the energy use in building operation is to focus the retrofit actions first on reducing the energy demand and carbon emissions and second on transforming the energy supply side in an efficient and low or zero carbon energy supply. The energy demand side includes all the energy that the building requires to operate. This reflects the energy needed for heating and cooling, the energy required for lighting and for equipment and appliances. The energy supply side refers to the energy delivered to the building. It reflects the energy delivered through the grid in different forms (electricity, gas and/or heat[14]).

By retrofitting the wide range of building components, services and systems that are part of the two energy sides it is possible to reduce to the energy consumed by buildings. A brief review of the retrofit measures to improve the energy efficiency of a building is presented in Table 1.

[14] Heat is delivered in the form of hot water or steam. The heat distribution network is known by the name of *district heating*.

Table 1 - Overview of retrofit measures for residential buildings.

Energy demand side	
Heating and cooling demand reduction	Building fabrics insulation and reduction of air leakage (walls, roof, attic, floor, windows & doors, draughts) Building services (efficient HVAC system, efficient DHW technology)
Electricity demand reduction	Lighting upgrade Energy efficient equipment and appliances
Energy management tools	Sensors, electrical meters, advanced control systems, energy analysis computer programmes, etc
Energy supply side	
Low carbon energy supply	Micro generation (renewable energy sources) Electric system retrofit Thermal storage

The different retrofit measures are discussed in the next sub-section.

3.3.1 Energy demand side

Building fabrics insulation and reduction of air leakage

Heat transmission through building elements is the cause for heating and cooling demand in buildings in order to re-establish the indoor thermal comfort. If the building would not have any heat losses through its elements, indoor thermal comfort would be preserved and no heat demand would exist. Since heating demand has the largest building energy end-use (see Section 2.2), to reduce transmission and ventilation heat losses is therefore the first step in any energy efficient retrofit project. The building elements with more heat losses are walls, representing 35% of the total building's transmission and ventilation heat losses, followed by the roof (25%) and the floor (15%). Draughts represent 15% (ventilation loss) and windows 10% of the total heat transmission and ventilation losses. Figure 9 shows the transmission and ventilation heat losses through the building envelope.

Air leakage through gaps (draughts) in the building envelope causes heat losses by ventilation. This uncontrolled airflow does not allow a proper control of air quality (i.e. humidity, temperature, pollutants, etc) unless large ventilation, heating and cooling systems are used to maintain comfort indoor conditions, which have also large operating costs. However, air leakage and infiltration are solved by simple measures, which will be next discussed.

Figure 9 - Transmission & ventilation heat losses through building envelope (Department for Communities and Local Government, 2006).

Insulation of the internal and external elements of a building has the effect of reducing heat flow through the elements, thus reducing the need for heating but also for cooling. Nevertheless it is important to bear in mind that insulation as a solution for reducing heat losses has its limits. Over insulation needs to be prevented, otherwise it can produce overheating in the summer. In short, the solution to reduce heat losses by transmission and ventilation should be comprehensive and holistic, taking into account the effects of different measures. Retrofit measures to address each building element and reduce heat demand are presented below.

- **Walls**

Energy Saving Trust (EST) argue in their report published in 2007, that internal wall insulation is the most cost-effective solution in a deep-energy retrofit and is also the easier to install. It is suitable for the cases in which the outer façade needs to be maintained in its original features, as in the historical buildings cases. But it has also some disadvantages, mainly internal living space loss (especially in small dwellings) and disruption for the occupants. External wall insulation is the most desirable solution for some type of walls (solid walls), although being more expensive (Xing, Hewitt, & Griffiths, 2011). Thermal bridging is more easily avoided and condensation risk is reduced. In addition to the problem of overheating, the continuous increase of insulation thickness causes other problems such as more complex design, construction and maintenance. To prevent this, many insulation materials with lower thermal conductibility have been developed like aerogel, multiple-layer insulation, transparent insulation, gas-filled insulation and vacuum insulation (Xing et al., 2011).

- **Roof**

According to EST (2007), lofts are the easiest to insulate. In some cases a large insulation thickness may be required to achieve the best practice U-value which can reduce internal space. In the case of flat roofs it is most economical to add the insulation when roof covering is being replaced. Green roofs[15] are considered another option to reduce heat demand in winter and prevent cooling demand in summer, since they act as an insulation layer. However it does not seem to be considered in retrofitting solutions, due to lack of research on materials to employ (Xing et al, 2011).

- **Floor**

Heat loss through floors depends on several factors: size, shape, type of floor and the conductivity of the ground below it. Different insulation thicknesses are required depending on the type of floor. Heat loss can be reduced up to 60% by placing insulation (EST, 2007).

- **Draughts**

This form of heat loss is due to heat leaks through gaps in the building envelope fabric, particularly in the joins of windows and doors. They can be strongly reduced by improving the air tightness of the building. Different authors (Xing et al., 2012; Thorpe, 2010; EST, 2007) argue that draught proofing is one of the most inexpensive, simplest to install and effective energy efficiency measures. The efficient materials to solve the problem include brushes, foams, sealants, draught excluders and tapes. Replacing windows and doors can also have a significant impact in reducing heat losses from draughts.

- **Windows & Doors**

The greatest impact of replacing these building elements comes from eliminating draughts. Best practice U-values require double glazing windows with low-e coating and argon fill, and an insulating frame between the layers of glass. In more ambitious refurbishment projects, as to achieve *Passive House*[16] standards, triple glazing windows are required. When replacing the windows, draught-stripping must be included in order to address heat leakage. Doors with insulated cores between the outer surfaces are recommended and should include draught-stripping as well. As with walls, avoiding thermal bridges is important and requires special attention when replacing both elements.

Building services

Energy use for space heating and cooling is the largest fraction of the total energy use for operation of the building (see Section 2.2). Reducing the heat transmission and (unwanted) ventilation losses significantly reduces the heat demand and therefore reduces to a large extent the energy use in a building. However, retrofitting building services can reduce even more the heat demand and also reduce the carbon emissions due to heating and cooling technologies. In the report "High-rise refurbishment" (2006), from the IEA, it is argued that independently of climatic regions in Europe, a reduction in the heating demand between 70 and 80% is achievable in high-rise European buildings. This reduction would be achieved by insulating building fabrics (>50%) but also by retrofitting building services (20 to 30%).

In order to achieve this additional reduction in the energy use of a building, the second step in a retrofit project should be to retrofit the technologies used for space heating and cooling. The retrofit measures to apply to increase their energy efficiency include insulating materials, replacing the energy sources (to more efficient and low carbon ones) or the total replacement of the technologies used for heating and cooling. These types of measures can reduce the heat demand to a much larger extent,

[15] A green roof is a lightweight, engineered roofing system that allows for the propagation of rooftop vegetation while protecting the integrity of the underlying roof (Spala et al., 2008).

[16] Passive House is a benchmark for energy efficiency in buildings. The concept is to improve the thermal performance of the envelope to a level that the heating system can be kept very simple (Feist et al., 2005).

elevating the building to higher standards regarding energy performance, as to achieve Passive House standards.

To achieve heating and cooling production technologies with significantly lower carbon that could contribute to achieve a carbon neutral building[17], a shift is needed from conventional heat-only gas or direct-electric heating and electric chillers towards systems that make use of passive sources, renewable energy sources or waste heat from power generation, in that order of priority (Hinnells, 2008). According to that, desirable heating technologies include heat pumps, micro-CHP (combined heat and power) and district heating. Heat pumps recover heat from different sources (air, soil or water) for use in space heating and/or cooling. Since most heat pumps are reversible they can be used for cooling as well as for heating. Despite their high initial system cost, these technologies have high efficiencies and can represent, in some cases, a good alternative to retrofit building heating technologies (Friedman, 2012). Micro-CHP can run on natural gas and its advantage is to produce simultaneously heat and electricity in the same power plant, which increases the overall efficiency of a CHP process when compared to conventional thermal power plants (Friedman, 2012). District heating, a system for distributing heat generated in a centralized location for residential heating requirements, is available and well developed in some European countries such as Finland, Denmark or Iceland (Persson & Werner, 2012; Euroheat & Power, 2013). Since it recovers waste heat from other industrial processes, it can be very efficient and cost-effective when applied to a whole street, area or neighbourhood, since communal systems have better economics (Burton, 2012). The cases in which there are other technologies in use (e.g. boilers), these should be retrofitted in order to increase their efficiency. However, in most cases, the selection of heating systems to retrofit is not straightforward. As Friedman (2012) suggests, when selecting a mechanical heating system, one should consider factors such as cost, efficiency and effectiveness.

Bioclimatic principles, such as passive solar technologies for cooling and heating (solar gains, optimization of daylight use), can significantly reduce the energy demand of a building and should be enhanced during the design and construction (Hinnells, 2008; Tzikopoulos et al., 2005). Domestic hot water (DHW) also represents a large fraction of the total energy consumption in buildings and retrofitting its technologies is fundamental. Whenever possible, solar water heating should be installed.

Due to the increasing air tightness of buildings, overheating problems are becoming more common. Natural ventilation, a form of passive cooling, can reduce significantly the cooling demand and has a good potential to avoid overheating problems in buildings. Furthermore it also improves indoor air quality and avoids problems derived from increased air tightness in buildings. Thorpe (2010) refers to several ventilation technologies: intermittent extract fans and background ventilators, passive stack ventilation, single room intermittent heat recovery ventilation, whole house mechanical ventilation with heat recovery, passive cooling and heat pumps.

In any of the cases mentioned above, it is important to notice that the electrical system may need to be renovated due to the replacement of technologies. For instance, the installation of renewable energy sources requires a new electrical connection to the grid.

Electricity demand reduction

Electrical lighting represents 30% of total domestic electricity consumption (see Section 2.2). Lighting energy use can be reduced by a large extent through the combination of day lighting, energy efficient lighting and control (Hinnells, 2008). Efficient use of day lighting by passive methods, both in building design and fabrics, reduce the need for electrical lighting and increases visual comfort for the occupants. Day lighting use together with the replacement of inefficient lights (e.g. incandescent

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[17] A carbon neutral building generates sufficient surplus of CO_2eq free energy (annually) that balances any purchase of grid energy (Newton & Tucker, 2010).

lights) by low energy lighting (e.g. Light-emitting diode [LED]) efficiently displaced in the space, and lighting control (e.g. sensors) represent the most cost-effective retrofitting solution for lighting. The electrical system may also need to be retrofitted in order to enhance the efficient display of lighting in the building.

Household appliances and equipments share a significant fraction of electricity consumption in domestic buildings. When compared to the total energy consumption they are a marginal share, although strongly increasing in the last years (see Section 2.2). Nevertheless is desirable for all the appliances to be "A" rated by the EU energy label for equipments and appliances.

Energy management tools

Energy management tools, such as sensors and energy meters connected to computer systems, are useful in monitoring and controlling the efficiency of the building services during the operation of the building. Smart meters, for instance, allow the monitoring in real time of how much electricity is being used, how much it costs, and of the temperature in the house. These tools encourage changes in the behaviour of the occupants and are able to detect whenever the optimal operating conditions are changed. Thus, they are important on the post-retrofit phase in order to monitor the energy performance of the retrofitted building, verify and measure the energy savings achieved, and ensure an efficient and effective operation (Ma et al., 2012; Hinnells, 2008).

3.3.2 Energy supply side

One fundamental step in an energy efficient refurbishment is to select the most efficient and low-carbon energy sources. Once the energy demand is reduced to the minimum possible, using the retrofit measures discussed in Section 3.3.1, the remaining demand should be met through the most efficient and low carbon technologies. According to the approach of the *Trias Energica* (Lysen, 1996), the solution would be to establish on-site low and zero carbon energy supply technologies (micro generation). Technologies of renewable energy sources such as solar thermal, solar photovoltaic, wind, geothermal and biomass can meet partially or totally the energy demand of the refurbished building. Otherwise, the clean use of fossil fuels should be encouraged.

Also the electrical system should be retrofitted given that in most cases it presents technical problems and it is no longer adequate in order to enhance other retrofitting solutions (e.g. lighting).

Seasonal thermal storage can be of great value to balance heat demand and the renewable energy sources supply (Xing et al., 2011). Energy production from renewable energy sources does not remain constant over time because it depends on the availability of the resource (e.g. sun, wind). Furthermore, the moment the resource is available and the energy is being produced may not always correspond to the moment the energy is being demanded by the building. In order to balance the supply with the demand, thermal storage can be used to guarantee the availability of energy during the days, months or seasons when it is needed.

3.4 Summary and conclusions

The concept of energy efficient retrofitting and its fundamental phases were discussed in this chapter. An energy efficient retrofitting focuses on reducing the energy use of a building in order to extend its life cycle and reduce its impact on the environment on the long-term future. To attain those goals, retrofit measures to achieve energy efficiency, the use of renewable energy sources and the clean use of fossil fuels were discussed. The fundamental phases of a retrofit project were discussed with particular emphasis on the project setup phase. During this phase several factors have an important influence on the scope, type and extension of the project: i) goals and targets of the project, ii) financial budget, iii) energy audit, iv) building specific characteristics and v) available retrofit technologies. In order to take into consideration all the constraints and limitations of the project, these factors require to be evaluated together, making of each project a complex optimisation problem. DSSs can be of great value performing this evaluation. As an approach towards a sustainable building design, energy efficient retrofitting should satisfy the social, economic and energy dimensions and they should therefore be considered in the analysis performed by the DSSs. In the next chapter, the importance of decision support systems on the evaluation of these impacts will be further discussed.

4. Decision support systems applied to energy efficient retrofitting

During the last decades, building energy simulation tools became a fundamental instrument to support decisions regarding the selection and integration of energy efficient measures in buildings (Rysanek & Choudhary, 2013). These tools coupled with decision support systems might play a relevant role in the design of buildings that satisfy energy, social and economic factors. They allow the simulation and comparison of the impacts of different retrofit options. Besides, they could provide detailed information on the energy performance of buildings before construction or renovation. A decision support system can be defined as "a tool that aids a user of the system in making choices (decisions) in a given situation" (Prevost, 2012). In that sense, DSSs applied to retrofitting play an important role that goes beyond the simple energy simulation of the building; they are capable of helping the user optimizing the whole energy system of the building according to his own quantitative and qualitative criteria, till one, or multiple, optimal solutions are reached. In a general way, they help the user making a decision that take into account a comprehensive range of factors. This is especially important in the case of an energy efficient retrofitting where a high number of factors affect the type of project and need to be considered: cultural, social, financial, energy, environmental, technological and regulatory.

As discussed in chapter 3, a sustainable retrofitting addresses the reduction of the three most used resources - water, energy and materials – during the life cycle of a building. On its side, an energy efficient retrofitting only addresses the energy dimension of the building. Therefore, the focus of the present research is on DSSs that assess energy efficient retrofitting and environmental and economic factors. The present chapter discusses the importance of using building energy modelling and discusses the specific application of decision support systems to energy efficient retrofitting.

4.1 The importance of building energy models

Building energy modelling consists in using computer-based tools to simulate the energy use of a building throughout a certain period of operation time. Through computer-based building energy models (BEMs) it is possible to simulate building energy physics in detail, energy flow paths and their interactions. There are many energy flow paths that occur continuously between the building and the exterior surrounding environment. These energy flow paths are caused mainly by three main heat transfer mechanisms - conduction, convection and radiation. In order to comprehend the nature behind these mechanisms, it is helpful to say that heat transfer is thermal energy in transit due to a spatial temperature difference (Incropera, DeWitt, Bergman, & Lavine, 2006). Thus, whenever a temperature gradient exists, in a medium or between media, heat transfer will occur. Conduction is the process of heat transfer through a solid or a stationary fluid (i.e. through a wall). Convection refers to the process of heat transfer between a surface and a moving fluid (i.e. electric space heater). Finally, radiation is the heat transfer between two surfaces, due to the emission of energy in the form of electromagnetic waves[18]. These three heat transfer processes take place simultaneously in such a complex environment as a building. The increased complexity of a system like this is that all the processes interact dynamically with each other. Although heat transfer processes are well known they are described by several complex equations that represent these systems. Furthermore, the fact that they are highly inter-related requires the application of "simultaneous solution techniques if the performance prediction is to be both accurate and preserve the spatial and temporal integrity of the modelled system" (Clarke, 2001). Thus, BEMs are complex programs, even when they use simplified analytical methods.

Although complex, BEMs are crucial for the simulation of the energy and environmental performance of a building, and for testing different technological solutions – both for design of new buildings and

[18] For further reading on this subject, Incropera et al. (2006) provide an excellent and complete introduction to the physical origins of heat and mass transfer.

for retrofitting of the existing stock – before implementation. Clarke (2001) provides an accurate summary of the importance of using building energy simulation by stating that it “allows users to understand the interrelation between design and performance parameters, to identify potential problem areas, and so implement and test appropriate design modifications”. Without BEMs architects and building services engineers had to rely on manual calculations using pre-selected design combinations which frequently led to oversized plant and system capacities and poor energy performance (Hong, Chou, & Bong, 2000).

Because of its potential in the design of buildings, building simulation has become standard practice, especially since the 1980’s, to evaluate and predict the energy performance of a particular building. This practice has resulted in an increased accuracy in building design thus ensuring an increasingly better energy performance of new and existing buildings. With the global concern to protect the environment and reduce energy use from fossil fuels, the challenge to professionals became, since 1990, to improve indoor air quality in the built environment, reduce its energy consumption and the negative impact on the environment. Thus, building energy models have gained acceptance as a routine analysis and design tools, and their use became commonplace in professional practice, rather than only in the research community (Hong et al., 2000). Their use became so fundamental and widespread that, for example, energy modelling has become a requisite for the certification and/or rating of buildings according to some energy and environmental assessment tools. For instance, Leadership in Energy and Environmental Design (LEED) tool, developed by the U.S. Green Building Council, requires the use of energy modelling to assess the energy performance of buildings and to quantify the energy savings derived from the proposed design (Rosenbaum, 2003). Also for the development of the national calculation method, in the EPBD context, European countries make use of building energy simulation programs to help in the certification of buildings.

With the growing concern for environmental protection, sustainable development and sustainable cities it is reasonable to argue that the design of sustainable buildings will continue to be a relevant research domain. Considering future trends of building simulation and modelling, several authors suggest that building simulation will become more demanded, often and widely applied in building design and analysis (Clarke, 2001; Hong et al., 2000; Wetter, 2011). Hong et al. (2000) and Wetter (2011) present as motivating factors for the future development of building simulation i) the increasing energy performance and comfort level required in buildings, ii) the importance of early design stages in the building energy performance, iii) the need to supervise the operation and maintenance of building services systems, iv) the need for integrated and multidisciplinary building design systems and v) the need to incorporate knowledge-based systems or decision support systems with the building simulation programs. The need to incorporate DSSs is due to the general limitation of simulation programs in providing suggestions to improve the building design and operation and run iterative processes that could satisfy the goals and targets of the user. This fact emphasizes the importance of this research for DSSs able to support the user in his decision on energy efficient retrofitting.

According to Hong et al. (2000), building simulation can be applied in the life cycle analysis of a building, including design, construction, operation, maintenance and management. They consider seven popular applications of building simulation:

- Building heating/cooling load calculation
- Energy performance analysis for design and retrofitting
- Building energy management and control system (EMCS) design
- Complying with building regulations, codes and standards
- Cost analysis
- Studying passive energy saving options
- Computational Fluid Dynamics (CFD)

Building simulation to calculate the “building heating/cooling load” is mainly used to size and select HVAC equipment, systems and plants. The popularity of this application is due to the heating/cooling load representing the largest fraction of the energy consumption of the operation of a building.

Analysis of the energy performance in order to design new energy efficient buildings or to retrofit the existing ones is enhanced by the evaluation of the annual building energy demand profile and part-load performance of major energy consuming equipment (e.g. building services). The economic savings can also be estimated for energy planning and management. Furthermore, innovative strategies to reduce the energy consumption can be simulated and assessed before implementation. EMCS design allows the monitoring and controlling of the operation of the building systems to ensure that thermal comfort and energy efficiency is maintained. This application is especially relevant after a deep renovation or in the case of large buildings with complex HVAC systems (e.g. non-residential buildings) to ensure the optimal energy operation of the building (see Section 3.2 and 3.3.1). Building simulation also plays an important role to design the building in compliance with national or local regulations, codes or standards. Performing a cost analysis for the several design options enables the user to choose between the cost-effective energy-saving alternatives. The study of passive energy saving options allows considering the feasibility of integrating design options that do not make use of mechanical sources such as day lighting, night ventilation, etc. The last popular application is CFD, used to study global warming, urban climate, microclimate, building ventilation, indoor air quality, indoor and outdoor thermal comfort, fire safety and smoke extraction. Building simulation using CFD software is gaining popularity due to new standards on health and comfort in the built environment and the need to design internal spaces and HVAC systems that meet the required standards criteria.

Some of the applications can be combined together to form more comprehensive simulation programs, namely through the use of cost analysis in conjunction with codes of practice and energy standards or with the energy performance analysis. In the same way, building heating/cooling load calculation is a fundamental part of the energy performance analysis for the design of retrofitting projects. Furthermore, the combination of these different applications should contribute for the integration of the multidisciplinary activities involved in building design. Most important, we must consider that the increasing performance and improved comfort of buildings made building systems become increasingly integrated, as discussed in Section 3.3. In order to tackle this evolution, building energy models must become more integrated and holistic to achieve a complete building design. Although the need for future research on this domain is fundamental, building simulation programs are already of standard use in the professional practice and have proliferated in the last decades. However, still few are in the public domain and accessible worldwide.

Within some of the most widely used simulation programs for building energy analysis are *TRNSYS*, *DOE-2*, *ESP-r*, *BLAST*, *EnergyPlus* (Kolokotsa et al., 2009). These tools are capable of simulating building physics in detail and provide a profound energy analysis[19]. However, they lack in decision support because neither they provide suggestions on the options to improve the energy and environmental performance of the building nor consider the aims of the user. Since they are not able of running iterative decision making processes, they force the user to run different simulations with different options and compare the results out of the interface. This can be time-consuming and result in ineffective decisions such as out-of-budget projects or the selection of less suitable retrofit technologies for the goals and targets of the user. The incorporation of decision support systems with energy simulation programs brings together the advantages of simulating in detail the energy performance of the building with the search for the optimal solution that reflects the criteria set by the user and that satisfy the economic, social and energy dimensions. This enables an iterative decision making process and supports the user in a more effective way. This development is fundamental to stimulate energy efficient retrofitting. Although recent, there is much ongoing research on DSSs applied to retrofitting and as a result of that, there are several tools available and being used. Because of their usefulness and effectiveness, DSSs were the focus of this research.

[19] For further understanding of the simulation programs in use, Crawley et al. (2008) present a comprehensive comparative survey of the features of the twenty major building energy simulation programs.

4.2 Application of DSSs to energy efficient retrofitting

The concept of decision support system is broad and has been under development over the decades (see Power, 2002). A simple and broad definition, yet useful for the present research, is to say that a DSS is a computer based system that facilitates the process of decision making. It is a tool that is built specifically to support the solution of a certain problem and therefore has the aim of improving the quality of the decision making process. According to Keen (1981), DSSs are designed to help improve the effectiveness and productivity of managers and professionals. Therefore they should be interactive systems. As Keen argues, the DSS do not automate the decision process and do not impose a sequence of analysis on the user. Instead, the user delegates the computation process and then evaluates the results and selects the next step in the process. That is to say that the role of the DSS is auxiliary and advisory in the process of choosing among decision alternatives.

In most cases, the characteristics of the problems for which DSSs are used impose design criteria. Due to that need of criteria, the DSS must be flexible, easy to use, responsive and communicative. It should handle varied situations, be simple and quick to use so it can ease the decision making process, do not impose a structure on the user and should work in a way that stimulate the dialogue between the user and the DSS since that quality together with the system output provide effective use of the support system. Four major components constitute DSSs: i) the user interface, ii) the database, iii) the model and analytical tools and iv) the DSS architecture and network.

DSSs applied to retrofitting have the chance of enhancing the decision making process in retrofit projects by improving their effectiveness, saving time, and providing better and efficient solutions. By allowing the prediction and testing of different technological solutions before real implementation, DSS for retrofitting is a significantly useful tool to improve energy performance of existing buildings. In addition, DSSs have the advantage of being a fundamental tool to support the user in the particular choices for each retrofit project. Clarke (2001) argues that the barrier to increase energy efficiency in buildings has less to do with technological constraints and more to do with ineffective decision-support. That is to say that the technologies available to energy efficiently refurbish a building are currently capable of achieving the goals of energy efficiency in the existing buildings through retrofit. Yet, the problem among different stakeholders (e.g. policy makers, house owners, financial institutions) consists in a lack of knowledge on how to implement the right technology. The suitable technology for each case is dependent on the many constraints a retrofit project can have and that affect the project setup phase, as discussed in Section 3.2. Energy efficient retrofitting solutions have to balance environmental, energy, financial and social factors (Diakaki, Grigoroudis, & Kolokotsa, 2008). Decision support systems can greatly improve the efficiency with which the technology is employed in each case, thus improving to a larger extent the effectiveness of the retrofit projects.

Regardless of its methodological approach, a DSS for building retrofitting should be capable of evaluating the current energy and environmental performance of the building and suggest retrofit alternatives according to the predefined criteria set by the decision maker. In order to do that, the DSS should follow an iterative decision making process, that include the performance of different steps, as suggested by Alanne (2004) (Figure 10). Firstly, there is the need to define criteria regarding the factors that affect the renovation of the building. These criteria will influence and define the alternatives that the DSS might suggest. In this phase of the process, the DSS should assess the energy demand, the consumption of the major energy consuming building services and the energy supply on an annual or seasonal basis. This analysis can be performed by using the results from an energy audit, which would be more accurate, but can also be performed by estimation through data such as the energy bills and the physical conditions of the building. The energy analysis allows the evaluation of the current energy performance and the identification of the areas with energy reduction potential. Together with the other constraints of the project and the user requirements (see Section 3.2), the criteria to develop the retrofit project is defined. Secondly, based on the criteria, different possible energy-efficient retrofit measures are identified, leading to retrofit alternatives possible to implement. As argued in Section 3.3, retrofit alternatives should consider acting on energy demand side and energy supply side by stimulating the clean use of fossil fuels, the use of renewable energy sources and the overall energy efficiency of the building. Thirdly, the assessment of the energy, environmental, financial and social impacts, for each retrofit scenario, should be performed. This evaluation is made by using energy simulation models, economic analysis and risk assessment methods (i.e. model and analytical tools). Finally, on the basis of the analysis given by the DSS, the decision maker can either take the final decision for the retrofit project and select a retrofit plan or, if none of the solutions is satisfactory, redefine the criteria and restart the iterative decision support process.

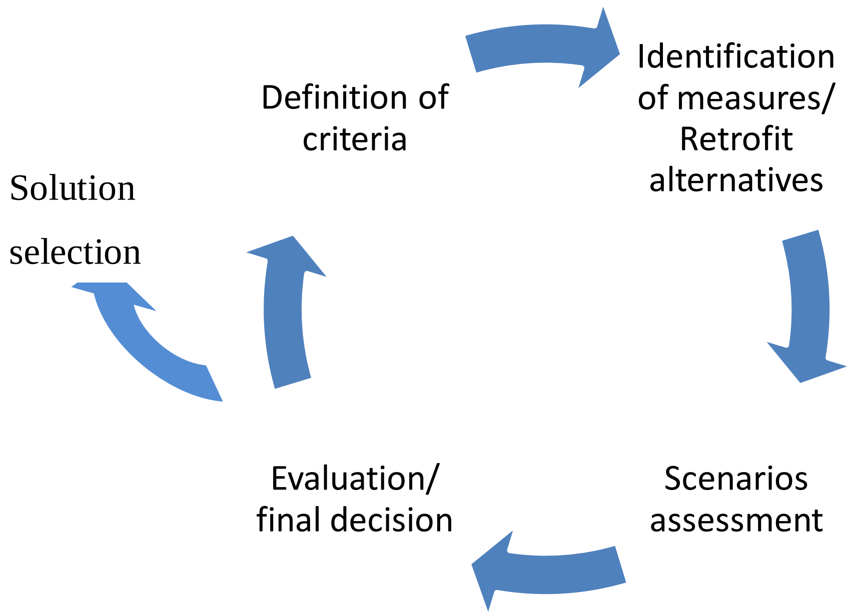

Figure 10 - Iterative decision making process at design phase of retrofitting (Alanne, 2004).

The aim with the decision making process is to achieve the best possible solution for the energy efficient refurbishment project. The definition of criteria should be up to the user. However, it is possible that some criteria could be conflicting with each other and also conflicting with the goal to achieve energy efficiency (e.g. preservation of the cultural and architectural heritage of the building). One way to handle this problem is the assignment of criteria weights to indicate their relative importance (Alanne, 2004).

The DSS must require data on the building specific characteristics, such as the physical conditions, the building elements, occupation patterns, and its annual and/or seasonal energy consumption. These data are fundamental for the DSS to perform a comprehensive energy analysis and identify energy saving areas in the building. This information is normally collected through an energy audit although, in its absence, the data can be collected by the user (e.g. through energy bills). However, in the absence of measuring instruments, some information is difficult to collect, such as the heat transfer coefficients (U-values) of the building elements, which are fundamental to an energy analysis. In order to require less building parameters and standardize methods in refurbishment projects, the use of building typologies is becoming common. Especially in Europe, the characterization of the physic and operational conditions of the existing building stock is becoming relevant. As argued by Dascalaki, Droutsa, Balaras, and Kontoyiannidis (2011), building typologies can be used for an in-depth understanding of the energy performance of the building stock, for the estimation of energy savings through refurbishment and to support energy saving policies. This characterization aids the classification of existing buildings into types of buildings with similar energy performance (mainly due to the practices of construction of certain decade). This also helps to define “packs” of refurbishment measures according to the needs of each building typology. DSSs that make use of building typologies can reduce the need for specific characterization of the building. Yet, real data concerning the energy use of the building is still necessary for a more flexible quantification and more reliable outputs (Yan, Wang, & Xiao, 2012). DSSs that make use of building typologies were also part of this research and were analysed and compared (chapter 6).

4.3 Summary and conclusions

Through building energy simulation it is possible to simulate building physics in detail and the energy flow paths that occur continuously between the building and the surrounding environment. This enables the prediction of the energy behaviour of a building under different conditions such as different construction elements, HVAC technologies and energy supply systems, thus, contributing to a great extent to the design of more energy efficient buildings. Although energy simulation programs are in development for decades and are of standard use nowadays, further research is needed. The lack of decision support makes the process of choosing among alternatives courses of action ineffective. Decision support systems can improve the decision making process, by stimulating iterative processes during the development of a retrofit project. They are auxiliary and advisory tools that help evaluating a comprehensive range of factors and choose the most feasible and adequate retrofit solution. In this chapter a brief history of building energy simulation tools was presented and the future challenges were discussed. One of the challenges is to incorporate decision support systems and knowledge based systems in building energy simulation programs to enhance the decision making process in building design. The applications of building simulation were discussed and its role on the design of energy efficient buildings became evident. Finally the iterative decision making process was depicted, highlighting the fundamental role of DSSs aiding the retrofit project.

Chapter 5 presents the selection of DSSs to compare further in this research: the methodology is described and the results are discussed.

5. Selection of the Decision Support Systems

As discussed in Section 4.1, through the simulation of the physical conditions of the building and of the energy flow paths that occur continuously between the building and the environment it is possible to evaluate and predict the energy behaviour of a building. The energy performance of a building depends to a great extent of the insulation of the building fabrics, the air leakage through the fabrics and the efficiency of the building services (Section 3.3). Therefore, modelling the effect of different energy efficient measures in the energy performance of the building allows choosing the most suitable retrofitting technologies in order to improve its energy efficiency. In addition, DSSs are able to offer an assessment of the social, economic, energy and environmental impacts that different retrofit measures will have in the existing building stock. Based on the analysis of these impacts, the DSS can provide different retrofit scenarios according to the criteria defined during the design phase. The user has then the information needed to either choose a retrofit project in accordance with his targets or repeat the iteration in order to achieve a better solution. The importance of this iterative decision making process performed by the DSS was discussed in Chapter 4, becoming clear that DSSs are crucial to aid different stakeholders choosing the most suitable energy efficient retrofitting project to a specific building, given the diverse existent constraints. The general benefit of using DSSs, as argued by Clarke (2001), is to give rise to a cheaper, quicker and better design process.

Throughout this thesis it has been argued that the widespread use of DSSs for retrofit analysis could encourage and support the users in the selection of the most suitable retrofit project. The contribution of standardized methods for retrofitting in Europe in addition to the generalized use of DSSs can contribute to accelerate the rate at which buildings are energy efficiently renovated. Nevertheless, there is not a single widespread DSS for retrofitting but instead many DSSs available. These DSSs are very diverse, differing to a great extent in their capabilities, and targeted for different types of users. It is then of fundamental importance to evaluate the existent DSSs for retrofitting, in terms of their capabilities and understand which features are most important to fully support energy efficient retrofitting in the European existing building stock. The aim for this research is to consider only the DSSs that analyse the energy performance of a building for retrofitting purposes. By evaluating and comparing several DSSs for retrofitting it was possible to assess the support that DSSs provides to the energy efficient retrofitting process in the European building environment. Due to time constraints and the impossibility of evaluating all the existent DSSs, it was necessary to first select the DSSs to evaluate. Section 5.1 explains the methodologies employed to select the DSSs for comparison for the purpose of this research. The results of this selection are discussed in Section 5.2.

5.1 Methods

Firstly, in order to select the decision support systems to compare in this research, a review regarding their availability was done. Secondly, decision criteria and key performance indicators were developed (5.1.1) in order to build a decision matrix, compare the performance of the DSSs and select the DSSs to be compared in this study (Section 5.2). The diagram of Figure 11 depicts the followed method.

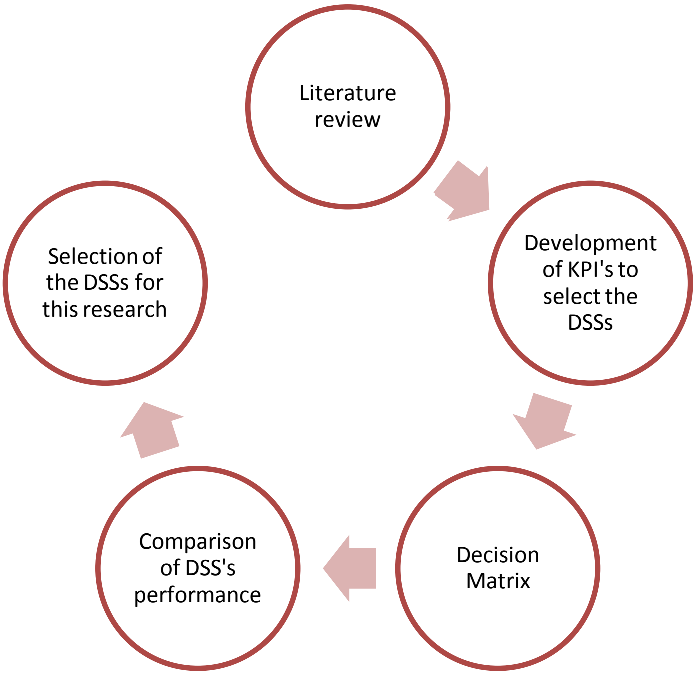

Figure 11 - Methodology followed for the selection of the DSSs to study.

As discussed in Section 4.2, there is a great amount of DSSs for retrofitting available to the public. The literature review on the existent DSSs was based on two types of tools: i) DSSs for energy efficient retrofitting and ii) DSSs for energy auditing. DSSs designed to analyse specific retrofit interventions, such as “green roofs”, solar energy or HVAC systems were not considered for the selection, since they lack a whole building approach and are thus too specific. A list of these DSSs is presented in Appendix II.

5.1.1 Criteria for selecting the DSS

A set of criteria and key performance indicators were developed in order to select the relevant DSSs to evaluate from the ones found during the literature research. These indicators reflect primary characteristics that a DSS to support energy efficient retrofitting in European countries should incorporate. Firstly, four relevant criteria were addressed: availability, applicability, policies and regulations compliance and system output. Secondly, key performance indicators within each category were developed according to their relevant and appropriate properties to the present research. In this section, a detailed description of each indicator is presented and justified.

Availability

Availability refers to the degree of use of a DSS. The use of a certain DSS can be limited by several conditions and therefore, become less available and less accessible to the general public. For the present research, the interest is towards the most available DSSs so, the less limiting factors to its use, the more widespread it might become. Two important indicators to assess this criterion are the language in which the DSS is presented and the conditions to acquire the software.

Indicator S1: Languages

Description and relevance: In order to have a widespread DSS in Europe that can be used by any user of its countries, language use is of fundamental importance. The ideal solution would be to have the interface of the DSS translated in every language in use in Europe or, at least, in the ones that have the largest number of speakers throughout Europe (e.g. English, French, German, Spanish, Italian). Unless this takes place in a case of a coordinated project involving all European countries, it is unlikely to happen. Another way to improve the number of users would be to use the English language, since it is the most widespread language throughout Europe (as a second language), and thus have a high number of speakers. English could therefore become the common language in DSS use. Hence, the use of English language was defined as a key performance indicator to select the DSSs to compare. Furthermore, also Spanish and Portuguese were considered since this research is of special interest for the University of Lisbon where Portuguese is the native language and Spanish is widely understood.

Indicator S2: Conditions to acquire software

Description and relevance: Raising awareness of cost-effective energy saving opportunities is fundamental to enhance action from the consumers (BPIE, 2011). In order to overcome the lack of knowledge and awareness, knowledge diffusion is a fundamental process to provide users with a more comprehensive understanding of what sustainability and energy efficient retrofitting means. Accordingly, DSSs can be very helpful in supporting information diffusion by i) providing real information about the building, ii) evaluating the energy, economic and social impacts of the retrofit measures and iii) providing solutions, through the presentation of retrofit scenarios. Nevertheless, DSSs only have a chance to play this role amongst stakeholders and effectively disseminate information if they are available and accessible to them. If one of the most relevant aims is to implement sustainable retrofitting in the largest fraction of the existing building stock, it is necessary to try to reach the highest amount of stakeholders and make them aware of the benefits. A free-software condition would make a DSS to spread more easily, rapidly, and widely, reaching a wider range of stakeholders. At least, for a first encouragement action towards a more sustainable building retrofitting approach, a free decision support system, even though in the case of a demo version of the complete program, could play an important role in knowledge diffusion and in raising awareness of the several different actors involved in the decision making process. Considering that the search for a widespread DSS is an aim of this research and that among the crucial characteristics for it to be broadly disseminated in the building environment is to be a free-software DSS, this was therefore one of the key performance indicators for the selection of the DSSs.

Applicability

Applicability refers to the extent of the building stock for which the DSS applies. For the purpose of this research, two different cases are interesting to address. Firstly, the location of the building stock assessed. Secondly, the type of buildings evaluated.

Indicator S3: European building stock

Description and relevance: The location of the building stock assessed by the DSS may influence some characteristics of the DSS. The more worldwide countries are added, the more difficult it gets to achieve standardized criteria to evaluate the factors that affect the retrofit project. Furthermore, it can also overload the database and make the DSS require long periods to simulate. However, a widespread DSS to evaluate the retrofit process in European buildings would be contributing to achieve the European targets of energy efficiency in the building stock, reducing the GHG’s emissions associated and improving the living conditions of the inhabitants. Thus, the aim was to focus on DSSs whose knowledge databases are European or, at least, included Europe. Although in most cases European DSSs are developed by European Institutions, it is not exclusive; there are also cases in which DSSs are developed under the scope of international projects, of which EU is an integral part, that also focus on the European building environment. What was relevant to be considered was whether the scope of the project, in which the DSS was developed, was focused on the European building stock. Thus, this indicator expresses weather the DSS applies to European countries.

Indicator S4: Residential building stock

Description and relevance: As discussed in chapter 2, residential buildings in Europe constitute 75% of the total floor area of building stock, thus representing the most significant energy consumers within the sector (65%). When using a DSS to meet European goals of transforming the building sector in a more sustainable one through retrofitting, focus on residential buildings is one significant step in order to be able to encompass the largest sub-sector. Moreover the residential building stock is easier to assess when compared with services sector, due to its lesser variation in building type, occupation and energy consumption patterns (BPIE, 2011). At least, seven different building types, providing different services, are identified within the non-residential sector. Hence it is predictable that each one of those building types is likely to need a specific DSS to assess their specific conditions (e.g. hospitals). On the other hand, residential buildings are essentially one of two types: single family houses and flats or apartment blocks. In accordance with the aforementioned, the second indicator to express the applicability is that the DSS is focused on the residential building stock.

Policies and regulations compliance

This criterion refers to the capacity of the DSS to return retrofit scenarios in which the design of the building is in compliance with the requirements of local building energy efficient policies and regulations. Although there are many energy efficient regulations in force in Europe, the European directive for the energy performance of buildings is especially relevant to assess in the DSSs.

Indicator S5: Energy performance of buildings

Description and relevance: Building energy labelling is a tool to enhance the energy efficiency of the residential building stock. It can encourage competitiveness within the sector and thereby foster building owners to take action by improving the energy efficiency of their buildings. The recent implementation of the EPBD made energy certification schemes for retrofitted buildings mandatory in all European countries. Therefore it is important for the purpose of selecting the tools for this research that among all policies and regulations, the calculation of the energy label is included as a technical feature in the DSS, by presenting the label attained according to the different retrofit scenarios. Decision support systems could play an important role in EPBD enhancement, by contributing to knowledge diffusion and improving the awareness of the user. On the one hand, the certificate is mandatory for buildings undergoing deep-energy retrofits so the DSS should remind it to the user by displaying the label for each scenario. On the other hand, this would improve the awareness of the user to energy efficient measures and eventually promote more ambitious retrofit projects. Accordingly, the key performance indicator to assess the criterion “policies and regulations compliance” is through the calculation of the energy label of the building.

System output

The system output criterion refers to the characteristics of the evaluation of the retrofit scenarios retrieved by the DSS. It is on the basis of that assessment that the user makes the final decision about the characteristics of the retrofit project (Section 4.2). In that sense, assessing the system output is relevant to guarantee the presence of three main parameters: retrofit scenarios, energy & environmental analysis and economic analysis.

Indicator S6: Energy & environmental analysis

Description and relevance: Reducing energy use in building operation constitutes one of the major goals to proceed to a retrofit intervention in a building. Energy and environmental analysis is therefore one of the strategic tools to evaluate and define the measures to implement. The analysis should be on the current energy performance of the building in order to be able to predict the future impact of the measures in its energy performance but also to compare the performance between different retrofit solutions. Accordingly, the energy performance should be assessed by the current energy use and by the expected energy savings in building operation. Environmental performance should be assessed by the current GHG’s emissions and the expected reduction in those emissions.

Indicator S7: Economic analysis

Description and relevance: Another aspect when considering a retrofit project is to reduce the costs associated with energy use in building operation. It is then relevant to quantify the reduction in the energy bill according to different retrofit measures. On the other hand, the necessary budget for retrofitting can be a limiting factor to implement the project. Consequently, the need for an economic analysis of the retrofit project is significant to enhance the decision making process. Accordingly, the DSS should assess the money savings with the retrofit project, the total budget necessary to its implementation and perform an economic analysis in the near future (e.g. payback period).

Indicator S8: Retrofit scenarios

Description and relevance: The retrofit project is defined based on different criteria, some of which are established by the building designer together with the costumer, while other are dependent on the building current conditions and characteristics (see Section 3.2). On the basis of these criteria, energy efficient retrofit measures are identified and evaluated, giving rise to different retrofit options to undertake. It is then evaluated, for each option, the impact of different factors: economic, social, energy and environmental. Due to the fact that these impacts may be related to each other and conflicting with the defined criteria, the possibility of a retrofit project able to satisfy all the different criteria is unlikely. In fact, what happens is that there are several different combinations possible, which satisfy the criteria up to different levels. These are the retrofit scenarios, which allow for comparison of different impacts according to the package of retrofit measures. Among the retrofit scenarios one exists that can be considered the “optimal combination” which will be selected by the project manager.

So far, we have discussed the relevant criteria to select the DSSs: availability, applicability, policies and regulations compliance and system output. Based on each criterion, eight key performance indicators were developed to select the DSSs for this research. Table 2 shows the summary of the criteria and respective indicators.

Table 2 - Key performance indicators for DSS selection.

Criteria	No.	Indicator
Availability	S1	Free-software
	S2	Languages (EN, PT, ES)
Applicability	S3	European countries
	S4	Residential building stock
Policies and regulations compliance	S5	Building energy label
System Output	S6	Energy & Environmental analysis
	S7	Economic analysis
	S8	Retrofit scenarios

5.1.2 Assessment

In order to select the DSSs, a decision matrix was built and the performance of the DSSs against the set of indicators was compared. Given the simple nature of the indicators, they were all assessed by their presence or absence in the DSSs. In the cases in which it was impossible to assess the presence of the indicator, it was assigned with *Not Available* (“N/A”). One point was assigned to the DSS for each indicator present, resulting in a final score for each one. The more present indicators a DSS had, the higher score assigned. Finally, the DSSs which this study focused on were selected based on the higher scores since it represented the higher number of indicators present. However, three boundary conditions were defined and applied. Firstly, due to time constraints, the number of selected DSS should not exceed five. Secondly, the absence of one of the first two indicators (S1 and S2) implied automatic exclusion since it represented an obstacle to the comparison. Thirdly, DSSs with “N/A” assessments were also excluded.

5.2 Decision matrix development

In this section the development of the decision matrix and the results from the selection of the DSSs are discussed.

Following the collection of DSSs, they were compared against the key performance indicators defined. In most cases, through the information presented in the specific websites of the different DSSs it was possible to assess the presence of indicators S1 to S4. Figures 12, 13 and 14 give an overview of the web pages of *Retrofit Advisor*, *TABULA* and *Energy Retrofit Tool for Buildings*, respectively. As figure 1 demonstrates, through the information available on the webpage of *Retrofit Advisor* it was possible to identify the free software condition, the use of English language and the assessment of European residential building stock.

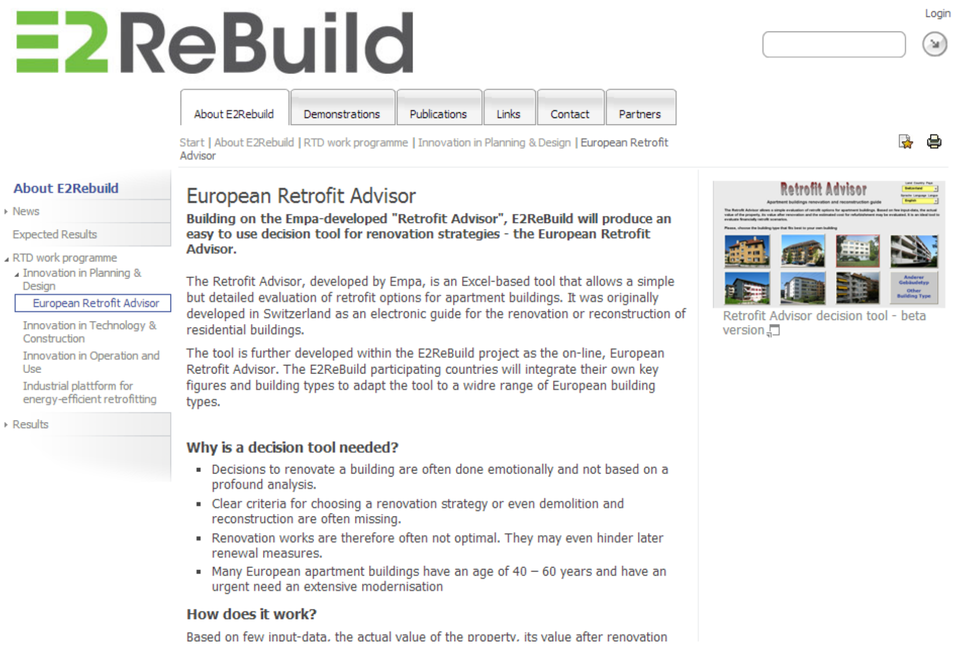

Figure 12 - *Retrofit Advisor* webpage.

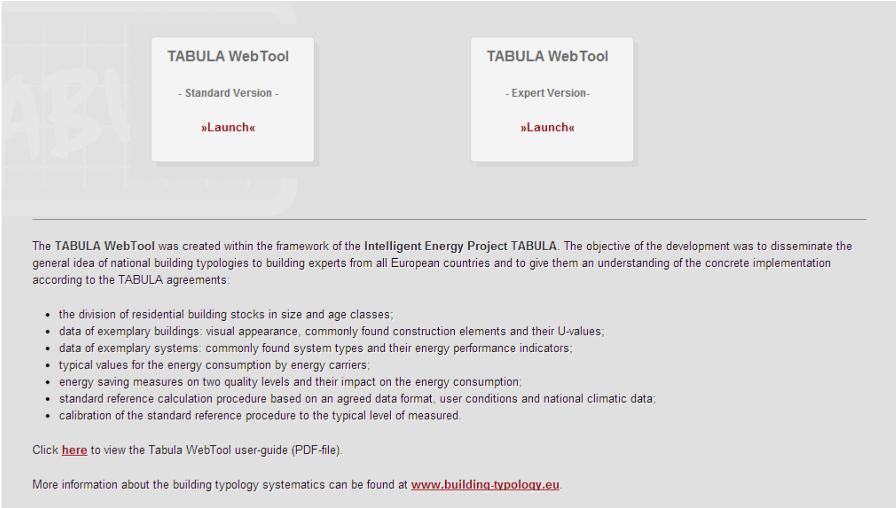

Figure 13 - Overview of *TABULA* webpage.

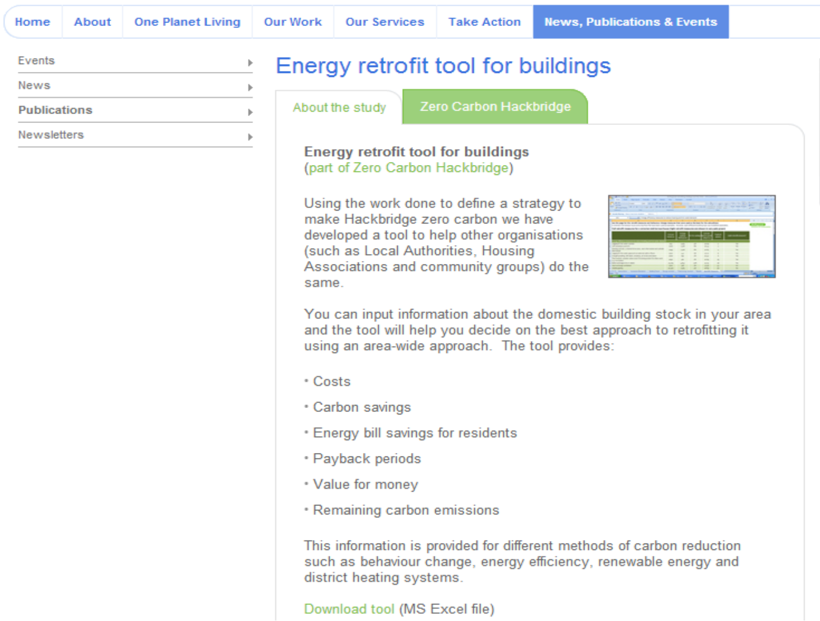

Figure 14 - Overview of *Energy Retrofit Tool for Buildings* webpage.

In order to assess the presence or absence of the remaining indicators (S5, S6 & S7) and S8 it was strictly necessary to run each DSS to check the incorporation of the feature. The cases in which the absence of the two first indicators made impossible to assess the presence of the remaining indicators, due to automatic exclusion, were assigned with *Not Available* ("N/A"). That was the case with *EnerCalC 2013*, *EQUER*, *Energy Explorer Utility of Buildings*, *EasyKenak*, *ReGreen*, *EA-Quip*, *Renoveren A+*, *Energy Auditing of Buildings* (EAB), *BEAM²*, *Energiebesparingsverkenner* and *EPIQR*. *OPTISOL* was assigned with "N/A" due to the inability to find the source for download. During the DSS running test to assess part of the indicators, one of the DSS available presented software errors. *COMBAT* DSS presents a software error which makes impossible for the user to proceed from the menu screen of the selection of retrofit measures to the results' screen. Although the software was run in different computers and the project leaders were contacted, the problem persisted. Thus making impossible to assess the type of output it provides to the user. For that reason, *COMBAT* DSS presents S6, S7 and S8 indicators as *Not Available.*

After assessing each DSS in accordance to each indicator, a decision matrix could be established (Table 3) and comparison between their performances could be easily addressed.

Table 3 - Decision matrix for DSS selection with DSS performance for each key performance indicator.

DSSs	Key performance indicators							
	Free-software	**Languages (EN,PT,ES)**	**European countries**	**Residential building stock**	**EPBD**	**Energy & environmental analysis**	**Economic analysis**	**Retrofit scenarios**
TABULA	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes
ICE (2.0.8)	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes
Retrofit Advisor (β version)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
EnERGo/IT-Toolkit	Yes	Yes	Yes	No	No	Yes	Yes	Yes
REDUCE	Yes	Yes	Yes	No	No	Yes	Yes	Yes
COMBAT	Yes	Yes	No	No	No	N/A	N/A	N/A
Energy Efficient Rehab Advisor	Yes	Yes	No	Yes	No	No	Yes	No
Energy Retrofit Tool for Buildings	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes
Generation	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes
OPTISOL	N/A	Yes	N/A	N/A	N/A	N/A	N/A	N/A
EnerCalC2013	Yes	No (German)	N/A	N/A	N/A	N/A	N/A	N/A
EQUER	Yes	No (French)	N/A	N/A	N/A	N/A	N/A	N/A
Energy Explorer Utility buildings	Yes	No (Dutch)	N/A	N/A	N/A	N/A	N/A	N/A
EasyKenak	Yes	No (Greek)	Yes	Yes	Yes	N/A	N/A	N/A
ReGreen	No	No (Italian)	N/A	N/A	Yes	N/A	N/A	N/A
EnergyIQ	Yes	Yes	No	No	No	Yes	Yes	Yes
EA-Quip	No	Yes	N/A	N/A	N/A	N/A	N/A	N/A
Renoveren A+	Yes	No (Dutch)	Yes	N/A	N/A	N/A	N/A	N/A
Energy Auditing of Buildings (EAB)	No	Yes	Yes	Yes	Yes	Yes	No	N/A
BEAM²	No	Yes	N/A	N/A	N/A	N/A	N/A	N/A
Energiebesparingsverkenner	Yes	No (Dutch)	Yes	Yes	Yes	Yes	Yes	Yes
RETScreen 4	Yes	Yes	Yes	Yes	No	Yes	Yes	No
Energy Profile Tool	Yes	Yes	No	No	No	Yes	Yes	Yes
AkWarm	Yes	Yes	No	Yes	No	Yes	Yes	Yes
EPIQR	No	N/A	N/A	N/A	N/A	N/A	N/A	N/A

N/A – Not available (information is not provided, impossible to access it);

General findings

From the review on the availability of DSSs, their comparison and selection, some comments regarding the expression of the indicators are relevant to remark.

Developers of the DSSs

It was observed that several DSSs were developed in the framework of research projects by leading research Institutions which efforts are to obtain solutions and achieve better understanding of how to assess the refurbishment process. During the period in which this research was developed, apart from private institutions in the USA, the two major institutions actively involved in projects developing these DSSs were the International Energy Agency [20] and the European Commission[21] through specific programmes focused on improving building sustainability. DSSs developed in the framework of specific research projects, involving diversified stakeholders of a specific region (neighbourhood, municipalities, etc), were also identified. Finally, several private companies in the building construction and refurbishment domains were also identified with DSSs developed and being commercialized.

Indicator S1: Languages

As for the languages, most DSSs used only English language, although several DSSs presented it as an option among other languages. In general, language options appeared to be directly dependent on the project scope in which they were developed. Nevertheless, they were not always translated to all the languages of the participant countries, as it would be expected.

Indicator S2: Conditions to acquire software

In a general way, it was noted that the availability of the DSSs were significantly diverse in its forms. DSSs developed in the framework of research projects were in most cases free-software, completely available and easily downloadable, whereas the ones developed by private companies were more likely to be sold. The free-software DSSs varied to a great extent in the forms in which they were made available, between MS Windows-based software (which may require a previous registration of the user), MS Excel-based software or Web-based software. Other cases found were: i) paid DSSs that provided access to a demo-version of the software, ii) DSSs that were sold only to a restricted group of stakeholders and iii) DSSs for the internal use of the private company (e.g. consultancy work).

Applicability (Indicators S3 and S4)

As for the applicability, there were DSSs focused on the building stock of a specific municipality, country, region of Europe or random group of countries all over the world. In general, it was noted a great variety of building stock locations assessment. Regarding the type of building stock assessed, it was noted the separation between the services and residential sector. Within the services sector, there were very specific DSSs, as for instance the case of DSSs for retrofitting of office buildings or DSS for retrofitting schools.

Indicator S5: Energy performance of buildings

As for the presence of the calculation of building energy label, it was noted that only a small fraction (2 out of 8) of the collected European DSSs presented the indicator, as it can be seen in Table 4.

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[20] For instance, IEA has developed an ongoing energy research and innovation programme named Buildings and Communities programme (http://www.iea-ebc.org/)

[21] At the EU level, EC has launched several research programmes among which we highlight the Intelligent Energy Europe (IEE) that has funded much research on the building sector (e.g. EPISCOPE project.

Table 4 - Year of release of the collected European DSSs and the presence of EPBD feature.

European DSSs	Year of release	EPBD
EnERGo/IT-Toolkit	2011	No
Energy retrofit tool for buildings	2012	No
Generation	2011	No
ICE 2.0.8	2011/2012[22]	Yes
REDUCE	2004	No
Retrofit Advisor (β version)	2011	Yes
RETScreen 4	1998/2011[23]	No
TABULA	2011	No

Seven of the seven European DSSs became available to the public in 2011 or 2012, whereas the one remaining (*REDUCE*) was developed in 2004. From the eight DSSs collected, only two presented the building energy label in their retrofit scenarios: i) *ICE (2.0.8)* released in 2011 and updated in 2012 and ii) *Retrofit Advisor* (β version) released in 2011. The fact that the other DSSs do not incorporate the calculation of the building energy label could be related with the recent recast of the European Directive for the energy performance of buildings (2010) which clarified and improved the labelling calculation methods, and with its consequent slow diffusion. However, as the other two DSSs confirm, it was already possible to incorporate the calculation of the energy label and, as the recast was introduced, update the calculation methods in the DSS.

System output (indicators S6, S7 and S8)

It was observed that for the most part, the DSSs presented the three indicators for the system output (retrofit scenarios, economic and energy & environmental analysis). Only *RETScreen 4* and *Energy Efficient Rehab Advisor* did not present retrofit scenarios, *ICE (2.0.8)* did not perform an economic analysis and *Energy Efficient Rehab Advisor* did not present energy & environmental analysis. Apart from these, the remaining DSSs were extremely varied in the content and form of the analysis as for example in the quantity of indicators, the presentation of the results or the organization of the interface.

Based on the decision matrix, the rule of automatic exclusion was applied and the DSSs that presented N/A assignments were also excluded to the inability of clear and specific future comparison. To the remaining DSSs a score was assigned, based on the present indicators, and the resulting DSSs were ordered on the basis of the higher scores. The results can be seen in Table 5.

[22] The first year refers to the year of release of the DSS and the second to the year of the last upgrade made to the DSS.

[23] *Idem.*

Table 5 - DSS ranking.

DSS	Score
Retrofit Advisor (β version)	8
TABULA	7
ICE (2.0.8)	7
Energy Retrofit Tool for Buildings	7
Generation	7
RETScreen 4	6
AkWarm	6
EnERGo/IT-Toolkit	6
REDUCE	6
EnergyIQ	5
Energy Profile Tool	5
Energy Efficient Rehab Advisor	4

Based on the established maximum of DSSs to compare, the five best scored DSSs were selected for the comparison: *Retrofit Advisor* (β version), *TABULA*, *ICE* (2.0.8), *Energy Retrofit Tool for Buildings* and *Generation*. In the next Section each DSS is further described.

5.3 Description of the selected DSSs

In this Section a description of each DSS is provided. It contains a resume of the project in which the DSSs were developed, a summary description of the DSS (goals and methods) and some relevant information such as the year of release, the interface language and the type of software. The documents associated with the release of the DSS (e.g. reports, guides, newsletters) are mentioned and links to their websites are given.

5.3.1 Energy Retrofit Tool for Buildings (BioRegional tool)

Type: MS Excel-based software tool

Developer: BioRegional Development Group (private organisation).

Project description: BioRegional is an international charity organisation, founded in the United Kingdom (UK) in 1994. The organisation focuses on improving the sustainable use of resources. Their work is based on research and education to make sustainability products and services affordable and easy for the people to adopt. The *Energy Retrofit Tool for Buildings* was developed in the framework of "Zero Carbon Hackbridge" (ZCH) project. Hackbridge is a suburb in the London Borough of Sutton committed to the "One planet living" project which aims to achieve living sustainability by 2025 ("What is One Plannet Living?", 2013). In the aim of defining a strategy to make Hackbridge zero carbon, BioRegional developed the tool initially to help Sutton's Local Authorities, Housing Associations and community groups identifying how they could retrofit residential buildings in their urban area. However, the development of the tool has also the intent of helping other regions to do the same.

DSS description: Since the goal of the project was to develop an area-based retrofit strategy for the area of Sutton targeted to community groups, the DSS allows selecting several buildings to describe the user's building stock in the community. The user is allowed to choose the buildings among several typologies, based on the ones existent in the region and classified into building size and construction year. The DSS then presents several methods to achieve energy savings and carbon reduction such as behaviour change, energy efficiency, renewable energy sources and district heating systems. The retrofit scenarios are provided for the whole building stock and are based on the methods aforementioned, alone or combined. The DSS organizes the scenarios into four options: full retrofit, light retrofit, connection to a district heating network and the combination of light retrofit with the connection to a district heating network. Furthermore, it considers five different types of primary energy sources for the district heating option. Overall it presents 12 retrofit scenarios for the selected building stock.

Year of release: 2012

Interface language: English

Building stock: Existent residential building stock in the area of Hackbridge (London, UK) and suitable to other UK areas.

Documents available: Project summary

Website of the developer: http://www.bioregional.com/

Webpage of the DSS: http://www.bioregional.com/news-views/publications/energy-retrofit-tool-for-buildings/

5.3.2 GENERATION

Complete name (subtitle): Green Energy Auditing for a Low Carbon Economy

Type: MS Windows-based software tool

Developer: European research project supported by the European Regional Development Fund, within the POWER programme framework. The participant EU regions involved were Andalusia (Spain), South-East England (UK), Emilia-Romagna (Italy) and Malopolska (Poland).

Project description: Generation project developed a methodology to help users carrying out energy audits of buildings, in a simplified manner. One of the outcomes of the project was the *Generation* DSS that allows users to simulate the energy performance of the buildings. It is targeted for building professionals (e.g. energy auditors).

DSS description: The DSS performs a simulation of the energy performance of the building, based on data about the constructive elements and energy supply system, entered by the user. In order to validate the results concerning the energy consumption of the building, the DSS compares the results obtained by simulation with the data from energy consumption invoice given by the user. After that, the user can choose from a list of energy efficient retrofit measures, apply them to the building and consult the expected results to improve its energy performance. In addition, the DSS offers the possibility of performing an economic analysis of the retrofit project. Finally, it retrieves a complete report containing all the inputs given by the user and the outputs simulated by the DSS.

Year of release: 2011

Interface language: English

Building stock: Schools, administrative, residential and health centre buildings existent in the four European regions involved in the project

Documents available: Project newsletters, “Recommendations for policy makers”, “State of the art analysis”, Methodology report, User guide

Website of the project: http://www.powerprogramme.eu/projects.php?project=GENERATION

Webpage of the DSS[24]:

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[24] The webpage of the DSS (http://www.environmentcentre.com/rte.asp?id=31) is unavailable so the webpage given is the source for download from one of the project partners.

http://www.aess-modena.it/index.php?option=com_docman&task=cat_view&gid=110&Itemid=53&lang=it

5.3.3 ICE (2.0.8)

Complete name: Informe de Conservación del Edificio y Evaluación energética (Building Conservation Report and Energy Evaluation)

Type: MS Windows-based software tool

Developer: Developed by the Valencia Institute of Building (VIB). Promoted and funded by the Ministry of Environment, Water, Urbanism and Housing of the Province of Valencia

Project description: The "Building conservation report and energy evaluation" is simultaneously the name of the DSS and the name of the major output: the report it retrieves to the user. This report is based on a technical inspection whose purpose is to achieve an understanding of the overall maintenance status of the building on its security, functionality and energy efficiency aspects, analyzing deficiencies, damages and signs of damages, in order to adopt the necessary measures and priorities for a future retrofit (Instituto Valenciano de la Edificación [IVE], 2011). *ICE* DSS is being used by the Regional Government to give grants to retrofit in an objective manner, thus, making *ICE* mandatory to apply to retrofit grants. It is targeted to building professionals and technicians.

DSS description: After the user entered the required information about the building constructive elements and energy supply system, the DSS performs an energy analysis on several retrofit measures and calculates the future energy label. To the latter, *ICE* DSS incorporates the calculation engine of the tool CERMA R. It also includes data from the Constructive Solution Catalog for energy retrofit. Both tools were developed by VIB. Finally, *ICE* retrieves the full report of building conservation and its energy evaluation.

Year of release: 2011

Interface language: Spanish

Building stock: Existent residential building stock of the Province of Valencia (Spain)

Documents available: User guide, Project summary, Other

Website of the VIB: http://www.five.es/

Webpage of the DSS: http://www.cma.gva.es/web/indice.aspx?nodo=72928&idioma=C

5.3.4 Retrofit Advisor (β version)

Type: MS Excel-based software tool

Developer: International research project in the framework of the Energy in Buildings and Communities (EBC) Programme from the International Energy Agency. The participant countries in the project were: Austria, France, Portugal, Sweden and Switzerland. Czech Republic and The Netherlands were also involved but are not included in the DSS. The DSS was developed by Swiss Federal Laboratories for Materials Testing and Research (Empa).

Project description: EBC Programme carries out research and development activities towards near-zero energy and carbon emissions in the built environment in order to accelerate its transformation towards more energy efficient and sustainable buildings and communities ("The EBC research programme", 2013). Within this framework, one of the many research projects undertaken (Annexes) was "Prefabricated Systems for Low Energy Renovation of Residential Buildings" (Annex 50, 2006 to 2011) in which *Retrofit Advisor* was developed. In order to address the problem of deterioration of buildings a new approach was developed, based on standardized and prefabricated renovation modules for facades and roofs (Zimmermann, 2012). Building typologies in the participant countries were also established. The results from the research project were incorporated in *Retrofit Advisor*. The DSS was designed for all type of users, non-professionals and professionals.

Within the framework of E2ReBuild project (January 2011 to June 2014) of the EU 7th Framework programme, *Retrofit Advisor* will be adapted - to a wide range of European building types - and fully developed for typical European refurbishment situations, and renamed as *European Retrofit Advisor*. However, at the time the present research was being developed, only the provisional test-version (beta-version) of *Retrofit Advisor* was available[25]. Therefore, in the following chapters, when further mentioning *Retrofit Advisor,* the author is referring to the beta-version of the DSS. On the website of the project is mentioned a reference guide to the DSS but due to the same reasons, the guide is not yet available.

DSS description: The DSS allows the evaluation and comparison of the economic, environmental and social impact of the building current situation, along with those of different renovation strategies (Zimmermann, 2012, p.17). Although it uses predefined building types and renovation scenarios, adjustments to the real situation can be made. It allows the user to choose between eight different renovation scenarios which combine insulation of building elements, heating, cooling and DHW technologies and changes in the architectural structure. Some of the renovation scenarios are based on the energy standards of several building energy labelling regulations developed in European countries (see Section 2.3). Besides renovation scenarios, *Retrofit Advisor* allows the user to consider two additional scenarios: repair and reconstruction of the building, as minimum and maximum scale interventions, respectively.

Year of release: 2011

Interface language: English, German and French

Building type: Residential apartment building stock existent in Austria, France, Portugal, Sweden and Switzerland

Documents available: Project summary, Retrofit simulation report, Building renovations case studies, Building typology and morphology, Retrofit module design guide, Retrofit strategies design guide, Other

Website of the project: http://www.empa-ren.ch/A50.htm

Webpage of the DSS:
http://www.e2rebuild.eu/en/events/workplan/pd/retrofitadvisor/Sidor/default.aspx

5.3.5 TABULA

Complete name: Typology Approach for Building Stock Energy Assessment

Type: Web software tool

Developer: International research project in the framework of the Intelligent Energy Europe (IEE) Programme of the European Union. The project partners were public research institutions from 13 European countries: Austria, Belgium, Bulgaria, Czech Republic, Germany, Denmark, France, Greece, Ireland, Italy, Poland, Sweden and Slovenia.

Project description: The objective of the project (2009 to 2012) was to disseminate the idea of national residential building typologies among building experts of all European countries, by developing a harmonised model for European building typologies. One of the key outcomes of the project was *TABULA* web tool where the residential building typologies are compiled and presented and serve as a data source for scenario analysis of energy savings achieved by retrofitting. As a

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[25] Project leaders were contacted about the current situation of the development of the new DSS and about the possibility of making a demo-version available to be used in the present research. However, no feedback was attained.

follow-up of the *TABULA* project, EPISCOPE project was launched in 2013 in order to continue and expand the building typologies concept in the retrofitting approach.

TABULA web tool is offered in two versions: the “standard version” and the “expert version”. The difference between the versions is that the “standard version” gives access to all information except the calculations, and the “expert version” gives direct access to the underlying data used by the first one. In the latter, building and HVAC system typologies can be selected, combined and then viewed on the light of several indicators. Essentially, the expert version allows the comparison between indicators of different building typologies. It is more a benchmarking tool, an additional feature of the standard version, and since them both use the same data, only “standard version” will be assessed during this research. Therefore, when referring to *TABULA* further in this research, the reference is made to the “standard version” of *TABULA* web tool.

DSS description: The building energy performance is assessed for the original state in each building typology. Then, energy savings potential obtained by retrofitting the thermal envelope and the HVAC system are presented, considering two predefined scenarios: “typical refurbishment” and “advanced refurbishment”. The first one includes retrofit measures which are commonly applied in each country and the second considers applying measures which correspond to the best available technologies.

Year of release: 2011

Interface language: English

Building stock: Existent residential building stock of the 13 countries involved in the project

Documents available: Project summary, Project synthesis report, Final report, National building typology brochure per country, National scientific reports, Others

Website of the project: http://episcope.eu/building-typology/

Webpage of the DSS: http://webtool.building-typology.eu/

5.4 Summary and conclusions

In this chapter, a set of criteria based on the specific aims of this research was established from which indicators relevant to assess in the DSSs were developed. Based on the decision matrix, it was possible to select five DSSs that are free-software, European, and focused on energy efficient retrofit in residential buildings. The selection of such DSSs contributes to understand how a DSS is able to support energy efficient retrofitting measures in Europe. In the next Chapter the comparison of the selected DSSs is developed and discussed.

6. Comparison of Decision Support Systems

This chapter focuses on the analysis and comparison of five European DSSs: *BioRegional*, *Generation*, *ICE (2.0.8)*, *Retrofit Advisor* and *TABULA*. All the DSSs were developed in the period 2011-2012, to assess energy efficient retrofitting of residential buildings. Two different comparisons of the tools were made. The first comparison assessed how the DSSs technically performed in evaluating the impact of retrofit measures and the second assessed how they performed from the perspective of the user. First conclusions are drawn after each comparison.

6.1 Comparison of general dimensions

The present research aims to compare how the previously selected DSSs (see Chapter 5) evaluate the impact of retrofit measures on buildings (see Chapter 1). As discussed in Chapter 4, this evaluation is performed by the DSS through the identification of the suitable retrofit measures for a particular building, the creation of different scenarios with those measures and the assessment of the impacts those scenarios will produce. In order to evaluate this process

in the selected DSSs it is relevant to assess: i) which specific information regarding the building the DSS requires, ii) which retrofit measures the DSS considers, iii) which retrofit scenarios the DSS retrieves, iv) how the DSS evaluates the energy, environmental and economic impacts of the scenarios. According to this, we have defined 6 dimensions which helped us to characterize the decision making process in the different DSSs:

- **Input dimension.** The input required by the DSS on building specific information in order to characterize it and assess its current building energy performance.

- **Technical dimension.** The retrofit measures considered to reduce energy demand and energy supply.

- **Output dimension.** Data retrieved by the DSS on the analysis made to the retrofit possible interventions.

- **Energy dimension.** Different retrofit measures produce different impacts in the reduction of the energy supply and demands of the building. The improvement on the energy performance of the building should be retrieved through an energy analysis.

- **Environmental dimension.** Current environmental impact of the building should be assessed as well as the expected reduction on that impact after the retrofit measures are simulated.

- **Economical dimension.** Economic analysis can evaluate the economic impact of different retrofit measures and help to choose the most cost-effective retrofit solution.

Based on these dimensions, indicators were developed to evaluate the performance of the selected DSSs. The units of the indicators were selected based on the standard units used in the literature and according to the International System of Units (SI). In the following section the different dimensions and their indicators are explained.

6.1.1 Indicators for comparison

The indicators developed in this research are a product of an extensive literature research. The literature review enabled a comprehensive overview of the input and output of a DSS for retrofit, its technical features, its user-support features and the technology, energy, environmental and economic evaluation methods in energy efficient retrofit of buildings. The goal was to define a list of indicators that could be considered essential to a baseline performance of any DSS for building retrofit and that could contribute to a generic method for their comparison.

Table 6 shows the summary of the four dimensions along with their specific indicators. Below, the relevance of each dimension is discussed and the indicators suggested are described.

Dimension A: Technical

Building retrofit can be divided in two main intervention areas: the energy demand side and the energy supply side (see Section 3.3). The two most important strategies to reduce the energy demand of a building consist on reducing the heating and cooling demand, by acting on the building envelope and the building services, and reducing the electricity demand, by acting on lighting and appliances. Accordingly, the DSS should address, at least, retrofit measures on the building envelope, the HVAC system and the DHW system. Although the electricity demand represents a minor share of the total energy consumption of the building (see Section 2.2), it should be considered by the DSS through retrofit measures applied to lighting. The energy consumption of the domestic appliances is more difficult to assess by a DSS[26] and will therefore not be considered as an indicator.

On the energy supply side, the strategy is to meet the demand using the most efficient and low carbon energy sources. This consists on using renewable energy sources, on the clean use of fossil fuels and on the use of the most efficient technologies for energy production. In that sense, the DSS should address the replacement of the existent energy sources for the most efficient and low carbon ones and the establishment of on-site production of energy through renewable energy sources (micro generation). The retrofit of the electrical system is not considered as an indicator due to the assumption that a DSS might not have enough detailed information about the building to propose the measure. Below, the list of indicators that quantify the *technical dimension* is presented.

A1. Building envelope

All the building elements should be addressed: walls, floor, roof, windows and doors. The retrofit techniques considered should include adding insulating materials, eliminating draughts and replacing windows for double and triple glazing windows and doors for insulated ones.

A2. HVAC system

The HVAC system should be entirely addressed with retrofit measures such as adding insulating materials, replacing the technologies and replacing the energy sources used.

A3. DHW system

The DHW system should be addressed with retrofit measures such as adding insulating materials, replacing the technologies and replacing the energy sources used. The aggregation of HVAC and DHW systems should also be considered in order to maximize their efficiency.

[26] It would require an extensive list of the installed capacity of the equipment and its usage in order to perform accurate calculations and suggest retrofit measures. Furthermore, the retrofit measures would be no more than to replace the equipment and recommendations on their use (e.g. avoid stand-by consumption).

Table 6 - List of indicators to characterize a DSS for retrofitting.

Indicators				
Dimension	**No.**	**Indicator**	**Sub-indicators**	**Unit**
A. Technical	A1	*Building envelope*	-	-
	A2	*HVAC system*		
	A3	*DHW system*		
	A4	*Lighting*		
	A5	*Micro generation*		
B. Input	B1	*Building characterization data*	-	-
C. Output	C1	*Retrofit scenarios*	-	-
D. Energy[27]	D1	*Current energy consumption*	*Total*	kWh/m^2.a
	D2		*By energy source*	kWh/m^2.a
	D3		*By end use*	kWh/m^2.a
	D4	*Current energy label*	-	Label
	D5	*Expected energy savings*	*per retrofit scenario*	kWh/m^2.a
	D6		*per retrofit measure*	kWh/m^2.a
	D7	*Expected energy consumption*	*Total*	kWh/m^2.a
	D8		*By energy source*	kWh/m^2.a
	D9		*By end use*	kWh/m^2.a
	D10	*Expected energy production*	-	kWh/m^2.a
	D11	*Future energy label*	-	Label
	D12	*Energy efficiency regulations compliance*	-	-
E. Environmental	E1	*Current CO_2 emissions*	-	kg CO_2e/ m^2.a
	E2	*Expected CO_2 emissions savings*	*per retrofit scenario*	kg CO_2e/ m^2.a
	E3		*per retrofit measure*	kg CO_2e/ m^2.a
	E4	*Expected CO_2 emissions*	-	kg CO_2e/ m^2.a
F. Economic	F1	*Current total energy costs*	-	€/a
	F2	*Retrofit budget*	-	€
	F3	*Investment costs*	*Total*	€
	F4		*per retrofit measure*	€
	F5	*CO2 reduction costs*	-	€/kg CO_2e
	F6	*Money savings*	*Total*	€/a
	F7		*per retrofit measure*	€/a
	F8	*Expected total energy costs*	-	€/a
	F9	*Payback period*	-	a
	F10	*Maintenance cost*	-	€/a
	F11	*Access to finance*	-	-

[27] Except for the indicators that refer to the energy label, which is calculated using the primary energy, all the other indicators refer to the final energy.

A4. Lighting

Combine day lighting, energy efficient lighting (e.g. LED) and control. Through this combination, 75-90% of lighting energy use can be reduced compared to conventional practice (Hinnells, 2008).

A5. Micro generation

Micro generation is the on-site production of low and zero carbon energy (heat and/or electric power) through renewable energy sources. These energy production technologies allow for the building to produce part of the energy it demands and therefore reducing energy demand from the grid.

Dimension B: Input

In order to identify retrofit measures for a specific building a DSS needs to have the building specific description. First, characteristics of the building construction and design are needed. Second, data regarding building energy consumption is fundamental. The first set of data provides information that describes the building physics and the second set of data provides information on the energy use of the building[28]. Evaluating the building physics is of fundamental importance to understand the thermal behaviour of the construction materials. Knowing the thermal behaviour of a building enables the calculation of heat gains and losses and thus, the prediction of the energy demand. To characterize the thermal behaviour of the building several indicators may be necessary to assess: i) construction age, ii) architecture, iii) area and volume, iv) fabrics, v) location, vi) solar exposure and vii) occupation profile. This set of data can be entered manually by the user or it can be characterized using typologies. Building typologies represent the aggregation of buildings into different categories according to their main characteristics.

B1. Building characterization data [typology/manual]

The set of data that characterizes the building is based on the main construction characteristics of the building such as construction date, geographic location and orientation, building type (single family house, flat, high-rise building), building area and volume and building fabrics, within others. This function can be of manual input or by selection of predefined building typologies.

Dimension C: Output

The essential output expected from the DSS is to identify areas with energy saving potential and suggest a set of retrofit measures to improve the energy performance of the building. Based on the criteria that affect the scope of the retrofit project, different energy-efficient retrofit measures are identified which result in retrofit alternatives possible to implement. It is fundamental to assess the technical features of those scenarios and how the comparison between them is performed.

C1. Retrofit scenarios [Automatic/Manual]

The retrofit scenario should contain all the retrofit measures considered and their technical specifications along with the evaluation of the energy, environmental and economic parameters (see categories D, E and F). If different scenarios are returned simultaneously as the final output, the DSS feature is considered automatic and assessed by the number of predefined scenarios retrieved automatically. Alternatively, if the DSS asks the user to create the retrofit scenario, it is considered a manual feature. In the manual option the DSS only presents one scenario at a time, forcing the user to save it, create other scenario and then compare them out of the DSS platform.

[28] The second set of data was evaluated through dimension D (energy analysis) where indicators to assess the energy use of the building were developed, among others.

Dimension D: Energy

It is essential to quantify the energy benefits in building energy consumption that result from retrofitting. After all, the main goal of an energy efficient retrofitting is to reduce the energy demand of a building. Quantifying energy consumption and savings plays a central role in i) the evaluation of the current energy performance of the building (baseline), ii) the evaluation of the impact of different retrofit measures in relation to the baseline, iii) ranking the different retrofit scenarios in terms of energy savings and iv) benchmarking the energy performance of the building. It is then of fundamental importance that the energy analysis encompasses both the current state of the building and the future state of the building after the implementation of the retrofit project. Furthermore it should quantify the savings that result from it.

In order to perform a comprehensive analysis of the energy consumption of a specific building, the quantification of the "total energy consumption" might not be enough. It is also fundamental to assess which type of energy is being consumed and where it is being consumed. As argued before (chapter 3), assessing the energy supply sources (coal, natural gas, etc) used in a building allows the development of a better strategy for decarbonising the energy supply and promoting the use of renewable energy sources. On the other hand, assessing the energy end uses (heating, cooking, lighting, etc) in a specific building enables the definition of priority areas to the retrofit intervention (i.e. the major sources of consumption). Therefore, the indicators "energy consumption by energy source" and "energy consumption by end use" were considered fundamental to a thorough energy analysis and were thus included as sub indicators of "Current total energy consumption" and "Expected total energy consumption".

We have argued before that micro generation should be considered as retrofit measure. Therefore, an indicator such as the "expected energy production" in the building through micro generation is suggested. Since the majority of buildings today do not produce their own energy, an indicator of the "current energy production" did not appear to be relevant for the time in which this research was developed.

When assessing the energy impacts of the retrofit project, it is relevant to assess the contribution of each retrofit measure on the whole energy savings produced by the retrofit project. It clarifies the effectiveness of the measure and aids the user selecting the measures to apply in the retrofit. On the other hand, it is also necessary to know the total amount of energy saved by the implementation of all the selected retrofit measures. Accordingly, the indicator "expected energy savings" should be expressed "by scenario" and by each "retrofit measure" alone.

Building energy labelling represents a more comprehensible form to assess building energy performance (see Section 2.3). It is mandatory in European countries, especially if the building owner is planning on selling the building, and it is a relevant benchmarking tool. It is thus to be included in the DSS, as indicators that assess the "current energy label" and the "expected future label" achieved with building retrofit. Although the EPBD represents the most important regulation in force at a European level, it would be relevant that the DSS would also check the compliance of the retrofit interventions with other regulations in force in the country. For that purpose the indicator "energy efficiency regulations compliance" is suggested.

Each indicator is further described.

D1. Current total energy consumption

The total current amount of final energy consumed in building operation during one year.

D2. Current energy consumption by energy source

The current annual final energy consumption of the building broken down into energy source (e.g fuel and electricity).

D3. Current energy consumption by end use

The current annual final energy consumption of the building broken down into energy end use (e.g. HVAC, DHW, appliances).

D4. Current energy label

Based on the current energy performance of the building the corresponding energy label should be assigned according to the scale in force in each country (according to EPBD).

D5. Expected energy savings per retrofit scenario

The amount of final energy expected to be reduced in the annual current final energy consumption of the building with the implementation of the retrofit project.

D6. Expected energy savings per retrofit measure

The amount of final energy savings that result from the implementation of each retrofit measure alone.

D7. Expected total energy consumption

The total amount of final energy expected to be consumed annually by the building after the implementation of the retrofit project.

D8. Expected energy consumption by energy source

The expected final energy consumption, after the retrofit, broken down into energy source (e.g fuel and electricity).

D9. Expected energy consumption by end use

The expected final energy consumption, after the retrofit, broken down into energy end use (e.g. HVAC, DHW, appliances).

D10. Expected energy production

The amount of energy expected to be produced annually by the building after the implementation of the retrofit measures.

D11. Expected energy label

Calculation of the energy label of the building (according to EPBD) expected to achieve through the implementation of the retrofit measures.

D12. Energy efficiency regulations compliance

The DSS should check the compliance with other energy efficiency regulations in force in the country, regionally or nationally.

Table 6 shows the units in which each indicator should be expressed. Although the DSSs may provide analysis on a monthly or seasonal basis, the standard time unit should be the year once it allows an analysis with less climatic fluctuations thus providing a more reliable basis for comparison. The unit most commonly used is energy (kWh) per square meter of the net floor area of the building (m^2) per year (a)[29]. EPB is expressed by the correspondent assigned label (the scale is different in every European country).

Dimension E: Environmental

Quantifying in terms of environmental gains is relevant considering that reducing global warming is the main reason for the effort on reducing the energy demand. CO_2 emissions should be quantified for the current energy consumption of the building, for the expected savings with the retrofit intervention and for the future energy consumption. Also the CO_2 emissions savings should be quantified both by scenario and by each retrofit measure alone. Therefore the indicators suggested are: “current CO_2 emissions”, “expected CO_2 emissions”, “expected CO_2 emissions savings per retrofit scenario” and “expected CO_2 emissions savings per retrofit measure”. The standard unit used for CO_2 emissions is

[29] Presenting energy values per square meter of the floor area allows quick comparison between different buildings and enhances building benchmarking.

kilograms of CO_2 equivalent (kg CO_2e) per square meter of the net floor area of the building (m^2) per year (a).

E1. Current CO_2 emissions

The amount of CO_2 emissions produced by the final energy consumption of the building during one year.

E2. Expected CO_2 emissions savings per retrofit scenario

The total amount of CO_2 emissions expected to be reduced annually with the implementation of the retrofit project.

E3. Expected CO_2 emissions savings per retrofit measure

The amount of CO_2 savings that result from the implementation of each retrofit measure alone.

E4. Expected CO_2 emissions

The amount of CO_2 emissions expected to be produced annually by the final energy consumption of the building after the implementation of the retrofit measures.

Dimension F: Economic

Economic analysis is needed to ensure the feasibility of the project. This is relevant in building retrofit due to budget restrictions of the building owner that determine whether the retrofit project can be implemented. The financial budget, alongside other factors, influences and contributes to determine the scope of the retrofit project (see Section 3.2). Thereby, it needs to be taken into account and analysed together with the other factors, in order to select the retrofit measures that are simultaneously energy efficient and cost-effective. Thus, “retrofit budget” is suggested as an indicator. Accordingly, in order to select the most suitable retrofit project amongst the scenarios suggested by the DSS it is fundamental to know the investment costs of each scenario which may oscillate around the retrofit budget initially defined. On the other hand it is also relevant to know the cost effectiveness of each retrofit measure that is part of the scenario. The two indicators proposed are the “total investment costs” and the “investment cost per retrofit measure”.

As with the energy and environmental analysis, to the economic analysis it is also essential to quantify the savings in the building energy budget that result from retrofitting. Accordingly, the economic analysis should encompass the current and future state of the building and calculate the money savings which are relevant to prioritize the different scenarios and aid the decision making process. The indicators suggested are the “current total energy costs”, the “expected total energy costs” and the “total money savings”. It is also relevant to assess the contribution of each retrofit measure on the whole money savings produced by the retrofit project. Again, it clarifies the cost effectiveness of the measure and aids the user selecting the measures to apply in the retrofit. Thus, the indicator “money savings per retrofit measure” should be present in the analysis. A different way of measuring the cost effectiveness of a retrofit project is to relate its costs with the associated CO_2 emissions reduction, through the “CO_2 reduction costs” indicator.

The simple payback period is a widely used method that allows users to quickly compare the cost-effectiveness of different investments. It consists in the period after which the capital invested is regained from the average cash flow surpluses generated by the project (Götze, Northcott, & Schuster, 2008). Therefore, the “payback period” is selected as an indicator for the method of the economic analysis.

The verification phase is a key stage of the retrofit project in which it is important to monitor and control the building services in order to ensure thermal comfort is maintained. Consequently this monitoring in the post-retrofit phase has an associated cost and should be considered by the DSS. The presence of the indicator “maintenance cost” is advised.

Deep-energy retrofits are most likely to be needed in aged and deteriorated buildings and once they constitute deep interventions they represent consequent high investment costs. In most cases, the only way the owner has to afford the needed retrofitting project is by applying to a bank loan. It would be important that the DSS could consider this frequent scenario by presenting some indicators concerning the eventual loan (e.g. bank loan conditions). Likewise, government financial support through energy efficiency programmes that assign grants and subsidies may as well be important to be considered by the DSS. In general, affordability to implement a retrofit project is one of the most common identified barriers to refurbishment projects and financial incentives the most effective driver to overcome it (Häkkinen, & Belloni, 2011). Recognizing this, DSS could contribute to overcome this barrier by gathering and displaying all the options available to finance the project. This feature would enhance the decision making process. The advised indicator to encompass this feature is “access to finance”.

Each indicator is further described.

F1. Current total energy costs

The amount of money currently spent, on an annual basis, with the total energy consumption of the building.

F2. Retrofit budget

The amount of money available from the client to invest in the retrofit project.

F3. Total investment costs

The total amount of money necessary to spend in order to implement the retrofit project.

F4. Investment cost per retrofit measure

The amount of money necessary to implement each retrofit measure alone.

F5. CO_2 reduction costs

The amount of money necessary to spend in order to reduce, through the retrofit project, the current emissions of CO_2.

F6. Total money savings

The amount of money expected to be saved in household’s current yearly energy expanses due to the implementation of the retrofit project.

F7. Money savings per retrofit measure

The amount of money savings that will result from the implementation of each retrofit measure alone.

F8. Expected total energy costs

The amount of money expected to be spent, on an annual basis, with the total energy consumption of the building after the implementation of the retrofit project.

F9. Payback period

The amount of years necessary to recover the amount of money originally invested (total investment costs).

F10. Maintenance cost

The amount of money necessary to be spent on a yearly basis in order to maintain good working conditions of the implemented retrofit project. For instance, the maintenance cost of the newly implemented heating & cooling technologies. This indicator may include the cost of the energy management tools implemented during the post retrofit phase (see Section 3.3.1).

F11. Access to finance

The available options to fund the total investment costs for the retrofit project are essentially of two natures: financial institution loans or Government financial support through subsidies or special loan conditions. Based on the total investment costs of the chosen retrofit project, conditions for an eventual bank loan could be presented by the DSS. Within these conditions, four are considered relevant from the perspective of the user: the amount of money to be loaned by the bank [€], the interest rate at which the loan is granted [%], the monthly rent to the bank [€/mo] and the total amount of payment years [a]. On the government financial support, the DSS should check if the project at issue meets the requirements and is eligible to be financially supported.

The units in which each economic indicator should be expressed are presented in Table 6. The euro was defined as the currency for the expression of the indicators since it is used in most of the EU countries. The time step defined for the expression of the indicators of the economic analysis was the year.

As mentioned in the beginning of this section, the underlying goal of the list of indicators developed for this research was to serve as a prerequisite for any DSS for retrofitting. This does not pretend to be an exhaustive list of indicators that the "best" DSS should include. However, to our knowledge, the selected indicators provide a good basis for comparison in order to get insights in the benefits and opportunity areas of the different DSSs under study. The next section discusses the results of the comparison of the DSSs against the list of indicators suggested in this research.

6.2 Results

The five selected DSSs were compared against the list of indicators. All the dimensions had the same weight in the comparison, as well as the indicators that constitute them. The indicators were assessed by their presence or absence in each DSS. Exception was made for the indicators of dimension B and C which were evaluated through their specific qualitative assessment. The intent of those dimensions was to discuss how the major input (building data) and output (retrofit scenarios) were organized and provided by the DSSs.

The DSSs were tested in order to check the presence of the indicators suggested in dimensions A, D, E and F. *BioRegional* and *ICE (2.0.8)* had predefined examples which were used to test their performance. In order to test *Generation* the example provided in the user guide was used. Regarding *Retrofit Advisor* and *TABULA*, a typology was chosen as an example for the comparison. The test of the DSSs enabled the comparison of each DSS against each dimension of indicators which is presented in Section 6.2.1. The comparison provided a quantitative analysis of the indicators included in each DSS. The final score of each DSS is presented at the end of Section 6.2.1. In Section 6.2.2 the DSS compliance with the units suggested to express the indicators from dimensions D, E and F is evaluated and discussed.

6.2.1 Comparison of the DSSs against each dimension of indicators

In this section the comparison of the DSSs against the list of indicators (Table 6) created for the present research (see Section 6.2.1) is presented. The comparison is first presented by dimensions (Tables 7 to 12) and finally the score of each DSS for the whole list of indicators is presented in Table 13.

Dimension A: Technical

As additional indicators, BioRegional presents several behavioural changes as retrofit measures.

Table 7 presents the comparison of the DSSs against the indicators of dimension A.

Table 7 - Comparison of the DSSs against the indicators of dimension A.

Dimension A Technical	**DSS**				
	BioRegional tool	***Generation***	***ICE (2.0.8)***	***Retrofit Advisor (β version)***	***TABULA***
A1. Building envelope	Yes	Yes	Yes	Yes	Yes
A2. HVAC system	Yes	Yes	No	Yes	Yes
A3. DHW system	Yes	Yes	No	Yes	Yes
A4. Lighting	Yes	Yes	No	No	No
A5. Micro generation	Yes	Yes	No	Yes	Yes

The following paragraphs give an overview of how each indicator was presented by the DSSs.

A1: Building envelope

The only indicator from the dimension of retrofit measures present throughout the DSSs was the “building envelope”. However, it was noted that three DSSs did not include retrofit measures applied to the doors of the building (*Generation, ICE* and *Retrofit Advisor*) and two DSSs do not mention draught proofing as a retrofit measure (*ICE* and *Retrofit Advisor*). Not considering retrofitting doors represents a flaw in the DSS, since insulation or replacement of doors is relevant to prevent heat losses (EST, 2007). Although the area of doors is relatively small when compared to the total area of the building, not considering their retrofit still represents a flaw for an accurate building analysis, since one building element is sufficient to induce heat losses. On the other hand, the fact that draught proofing is not mentioned may be due to the fact that is included in the so-called “insulation measures”.

A2 & A3: HVAC and DHW systems

Exception made for *ICE (2.0.8)* every other DSS presented retrofit measures for both the HVAC and DHW systems. In a general way, they all consider adding insulating materials, replacing the technologies and the energy sources. Changing heating controls (e.g. thermostats) is also considered. Furthermore they admit the possibility of associating the two systems.

In addition to the retrofit of hot water piping, which all the DSSs consider, *Retrofit Advisor* also considers the retrofit of the entire water piping. Although *ICE (2.0.8)* does not consider retrofitting HVAC and DHW systems, it considers the retrofit of the water system.

A4: Lighting

Only *BioRegional* and *Generation* considered lighting as a retrofit measure. In the two DSSs the user has the option of replacing the type of lighting for a more efficient one.

A5: Micro generation

Exception made to *ICE*, every DSS considered micro generation as a retrofit measure. Solar thermal and solar photovoltaic were an option in all the DSSs. In addition, *TABULA* also presented the option of a ground source heat pump and *Generation* considered all renewable energy sources (cogeneration, wind, solar, etc).

Dimension B: Input

Table 8 presents the qualitative assessment of the DSSs against the indicator of dimension B.

Table 8 - Comparison of the DSSs against the indicators of dimension B.

Dimension B Input	**DSS**				
	BioRegional Tool	***Generation***	***ICE (2.0.8)***	***Retrofit Advisor (β)***	***TABULA***
B1.Building characterization data	Typology	Manual	Manual	Typology	Typology

Only two out of five DSSs asked manual input regarding building data. Working with building typologies appears to simplify the analysis and the necessary input that otherwise would be an extensive and time-consuming process, as it is in the case of *Generation* and *ICE (2.0.8)*. These two DSSs require a detailed description of the building design, fabrics and equipment to be able to provide an accurate analysis. This might be a problem since the user is not aware of many of the characteristics of his building. On the other hand, typologies appear to lack specificity because they focus on generalizing characteristics of the building stock. Among the DSSs compared the combination of a building typology and a manual input seemed the most suitable approach. It saves time to the user on the specific and technical parameters of the building but still guarantees the adaptation of the typology to the real situation to some extent. The DSSs that use this combination allow some parameters of the building typology to be changed such as the energy consumption, the characterization of building services and the general characterization of the building design. This approach was observed to a great extent in *Retrofit Advisor* and to a lesser extent in *BioRegional*, which only allows adapting the annual energy consumption by energy source. *TABULA* allows the user to select the building typology and the HVAC and DHW systems typology. Apart from the selection of the two typologies, the DSS does not allow adapting the characterization of the building.

Dimension C: Output

Table 9 presents the assessment of the DSSs against the indicator of dimension C.

Table 9 - Comparison of the DSSs against the indicators of dimension C.

Dimension C Output	**DSS**				
	BioRegional Tool	***Generation***	***ICE (2.0.8)***	***Retrofit Advisor (β)***	***TABULA***
C1.Retrofit scenarios	Automatic [12]	Manual	Automatic [6]	Automatic [3]	Automatic [2]

Amongst the DSSs that automatically generate retrofit scenarios, *Retrofit Advisor* is the only one in which the user has freedom to change parameters of those scenarios. The DSS has three options by default: repair, retrofit and reconstruction which appear to correspond to a small, medium and large intervention in the building. However, most of the input allows changes: retrofit measures, extension of the building (e.g. adding floors), selection of energy sources and "social aspects".

BioRegional, *ICE (2.0.8)* and *TABULA* do not allow any interaction between the user and the DSS when creating the scenarios. In *BioRegional* it is difficult to understand clearly which measures are considered in each different scenario. The DSS only provides the general description of the scenarios and shows an example list of retrofit measures for just two of the many typologies. Therefore, the description of the scenarios lacks specific data. On the other hand, the DSS is very specific in its focus on district heating: i) ten out of twelve scenarios consider the connection to the district heating network as the energy source and ii) the main difference between the 10 scenarios is in the energy source powering the network. Apart from that, the other two scenarios appear to be based on the extension and scale of the retrofit intervention: i) "light retrofit" corresponding to a conventional retrofit and ii) "full retrofit" corresponding to a deep-energy retrofit.

ICE (2.0.8) identifies the main retrofit intervention areas (e.g. windows, walls, floor, etc) and presents for each one of them several options of retrofit measures to tackle the problem. It does not either provide the option of selecting the measures or a scenario with different measures regarding energy demand and energy supply. Instead, the DSS suggests retrofit scenarios for each one of the priority intervention areas alone. This was not expected to find because this analysis ignores the impact that different retrofit measures applied together can produce in improving the energy performance of a building.

TABULA presents two retrofit scenarios (usual and advanced) and, like the other DSSs, they could be compared to a conventional retrofit and a deep-energy retrofit. The characteristics of the two scenarios are well described in the DSS and the information is presented in a clear and organized manner. However, because the only input the DSS asks is the selection of the building and HVAC system typologies, it lacks interaction with the user and thus it does not enhance the decision support process.

Generation is the only DSS with manual scenarios. The user has to create its own scenario by choosing from a predefined list of retrofit measures and by defining the new parameters. Then, the DSS repeats the analysis it had already performed for the current situation and presents the results together for comparison. The user can create as many scenarios as he intend to, since the DSS will always present the different analysis in the same final report. The method presented by *Generation* is well organized and clear. On the other hand, it is also of a high level of difficulty considering that the average user is not acquainted with the impact of the retrofit measures and the thermal behaviour of a building and most of all, with the current retrofit needs of the building. As discussed in Section 4.2, the identification of retrofit measures and scenarios is part of the iterative decision making process and should not be performed solely by the user.

The report of the analysis of the retrofit scenarios should be retrieved in a type of document that the user could save and consult outside of the interface of DSS. *BioRegional* and *Retrofit Advisor*, because they are MS Excel-based software, are not capable of retrieving that kind of report. The user is forced to open the DSS to consult the results. This also results in more confusion in the presentation of the results. *TABULA*, *ICE (2.0.8)* and *Generation* provide excellent reports that contain all the technical parameters of the analysis performed. Except for *TABULA*, they also provide the comparison between the scenarios (for *Generation*) and the retrofit measures (for *ICE*).

Dimension D: Energy

Retrofit Advisor presented the highest score in the energy analysis, with 92% of the indicators suggested by this research. The only indicator absent in the DSS was the "energy savings by measure". Because this indicator is part of the underlying calculation for the savings of each scenario it could be easily added. It was also the only DSS that presented energy efficiency regulations compliance. *Generation* and *TABULA* presented approximately 50% of the indicators suggested, *ICE* 33% and *BioRegional* just 25% of the indicators.

The DSSs differ to a great extent in the content of the energy analysis. One specific example is the calculation of the total energy consumption and their break downs, both for the current and the expected situation. The end use and energy source breakdowns allow specific analysis whereas total final energy consumption allows general analysis and easy comparison between the current and the future state of the building. The consistence of the three analyses together is relevant in order to obtain accurate results. By comparing the three indicators it was observed that each DSS provides different analyses by breaking down the energy consumption by end use in a particular way. For example, *BioRegional* and *Retrofit Advisor* break down energy consumption into heating and DHW (together) and electricity, but do not specify the electricity breakdown. *Generation* provides the breakdown in cooling, heating, DHW, lighting and equipments while *ICE (2.0.8)* provides the breakdown only in cooling, heating and DHW. Since *ICE* does not present the breakdown by energy source the user does not know if the HVAC and DHW systems are powered by fuel or electricity. *TABULA* breaks down energy consumption in cooling, heating and DHW but does not consider equipment and appliances. The fact is that the expression of the energy consumption is far from being a standard process and that different analyses are possible. However, assessing together different building services and/or ignoring the consumption of some end uses may lead to inaccurate analysis and misleading results because different end-uses represent different equipment and thus, will need distinct retrofit solutions. Considering that analysing energy consumption is the basis for an accurate identification of the intervention areas and for a correct and efficient selection of the retrofit technologies to employ, it is extremely relevant that the DSS is able to comprehensively assess the energy use of the building.

There were also differences between the presence of the energy savings and the current/expected energy consumption. *TABULA* and *Generation* presented the current and expected energy consumption but did not calculate the energy savings, which is a simple calculation and useful for a quick analysis. *BioRegional* and *ICE (2.0.8)* only presented the energy savings per retrofit measure. The lack of the total current and expected energy consumption makes impossible to reference the savings and to benchmark the energy performance of the building. Furthermore, the energy savings per retrofit scenario are not the simple addition of the energy savings per retrofit measure and thus is an important indicator missing in the two DSSs.

Two indicators that were not suggested by this research were consistently observed throughout the DSSs: i) energy demand (all DSSs) and ii) total primary energy (*Generation* and *TABULA*). In fact these two indicators are relevant for some energy analyses. The energy demand of the building is the difference between the energy losses and the energy gains through the building elements. In other words, it is the energy the building needs to compensate the losses through the building elements (see chapter 4). Except for other minor losses that might occur in the equipment of the building, it is similar to the final energy consumption. On the other hand, the total primary energy is a relevant indicator for assessing the efficiency of the energy sources used by the building and the efficiency of the energy distribution grid. It might raise awareness on the user to a decentralized and sustainable energy production. Nevertheless, when compared to the list of indicators suggested these two indicators are secondary for the energy analysis. The indicators suggested in this research are adequate to perform both the analysis of the final energy consumption and of the energy supply.

Table 10 presents the comparison of the DSSs against indicators of dimension D.

Table 10 - Comparison of the DSSs against the indicators of dimension D.

Dimension D Energy	**DSS**				
	BioRegional tool	***Generation***	***ICE (2.0.8)***	***Retrofit Advisor (β)***	***TABULA***
D1. Current total energy consumption	No	Yes	No	Yes	Yes
D2. Current energy consumption by energy source	Yes	Yes	No	Yes	Yes
D3. Current energy consumption by end use	Yes	Yes	Yes	Yes	Yes
D4. Current energy label	No	No	Yes	Yes	No
D5. Expected energy savings per retrofit scenario	No	No	No	Yes	No
D6. Expected energy savings per retrofit measure	Yes	No	Yes	No	No
D7. Expected total energy consumption	No	Yes	No	Yes	Yes
D8. Expected energy consumption by energy source	No	Yes	No	Yes	Yes
D9. Expected energy consumption by end use	No	Yes	No	Yes	Yes
D10. Expected energy production	No	No	No	Yes	Yes
D11. Expected energy label	No	No	Yes	Yes	No
D12. Energy efficiency regulations compliance	No	No	No	Yes	No

Each indicator is discussed below.

D1. Current total energy consumption, D2. Current energy consumption by energy source & D3. Current energy consumption by end use

The way of presenting the energy consumption is extremely varied throughout the DSSs, being energy consumption by end use the only indicator present in all of them. *BioRegional* does not express clearly the total energy consumption although it presents the energy consumption of the building both broken down by energy source (fuel and electricity) and by end use (heating and electricity). *Generation* presents the three indicators where the end use is divided in lighting, equipments and HVAC and DHW. *ICE (2.0.8)* only presents the energy consumption by end use, divided into heating, cooling and DHW. *Retrofit Advisor* presents the three indicators where the end use is divided into HVAC & DHW and electricity. Finally, *TABULA* also presents the three indicators, where the end use is divided into heating, cooling and DHW.

D4. Current energy label & D11. Expected energy label

Only *ICE (2.0.8*) and *Retrofit Advisor* included energy label as an indicator. This was unexpected since by the time the DSSs were released or updated the European building energy labelling was implemented and recognized by each country.

D5. Expected energy savings per retrofit scenario

This indicator is presented only by *Retrofit Advisor. Generation* and *TABULA* present both the current energy consumption and the expected energy consumption but they do not express clearly the difference between the two values (i.e. energy savings). The inconsistence of this method is that it compels the user to do the calculations on its own which do not agree with the purpose of using a DSS.

D6. Expected energy savings per retrofit measure

This indicator is present in *BioRegional* and *ICE (2.0.8)*.

D7. Expected total energy consumption, D8. Expected energy consumption by energy source & D9. Expected energy consumption by end use

It was to expect that the pattern observed in the expression of indicators D1, D2 and D3 would remain in D7, D8 and D9. However, as mentioned, the expression of the energy consumption is extremely varied throughout the DSSs. Both in *BioRegional* and *ICE (2.0.8)* none of the indicators of expected energy consumption is present. Only the DSSs that presented the three indicators maintain the pattern and present the three indicators for the expected energy consumption.

D10. Expected energy production

Except for *ICE*, the DSSs assumed micro generation as a retrofit measure (dimension A), included the measure in the scenarios but only *TABULA* and *Retrofit Advisor* presented the “expected energy production” from micro generation as a percentage of the “expected final energy consumption” after the implementation of the retrofit project.

D12. Energy efficiency regulations compliance

The only DSS presenting this indicator is *Retrofit Advisor*. When considering the reconstruction scenario, the DSS asks the user to choose the “aspired energy standard” for the building suggesting the compliance with the SIA standard, the Minergie and the Minergie-P standards (see Section 2.3).

Dimension E: Environmental

BioRegional presents all of the suggested indicators. *ICE* does not present the expected savings by scenario because it does not present scenarios as defined by this research. The remaining DSSs present the current and the future CO_2 emissions but do not present the savings.

As additional indicators, *Retrofit Advisor* presents an “Eco-indicator” in the evaluation of the environmental impact (per m^2 and year) for each scenario. This indicator is expressed in “points” for which, unfortunately, the DSS provides no explanation. The DSS also presents the current and expected emissions both for the operation and construction (retrofit) phase of the building.

ICE (2.0.8) also presents two additional indicators: i) the current CO_2 emissions broken down by end-use and ii) the current CO_2 emissions associated with the heat losses through the elements of the building envelope.

Table 11 presents the comparison of the DSSs against indicators of dimension E.

Table 11 - Comparison of the DSSs against the indicators of dimension E.

Dimension E Environmental	**DSS**				
	BioRegional tool	***Generation***	***ICE (2.0.8)***	***Retrofit Advisor (β)***	***TABULA***
E1. Current CO_2 emissions	Yes	Yes	Yes	Yes	Yes
E2. Expected CO_2 emissions savings per retrofit scenario	Yes	No	No	No	No
E3. Expected CO_2 emissions savings per retrofit measure	Yes	No	Yes	No	No
E4. Expected CO_2 emissions	Yes	Yes	Yes	Yes	Yes

Dimension F: Economic

The majority of the DSSs appear to focus primarily on the energy and environmental analysis, making of the economic analysis a secondary one. *Retrofit Advisor* presented the highest score on the economic analysis, with 64% of the indicators of the dimension. It was followed by *BioRegional*

(55%), *Generation* and *TABULA* both with 18% and, as expected from the selection of the DSSs (see chapter 5), *ICE (2.0.8)* with none of the indicators present.

Retrofit Advisor has the most complete economic analysis. The absent indicators are the money savings (by scenario and measure) and the CO_2 reduction costs. Instead of the payback period it uses the discounted cash flow method. It is the only DSS that presents the maintenance cost and the retrofit budget. The latter is an indicator of much relevance, since is perhaps the only indicator of the list suggested that reflects the targets and goals of the user. As additional indicators of the economic analysis, the "site value of the property", the "insured building value" and the "loss of rent due to retrofitting" are presented by Retrofit Advisor.

BioRegional focuses on the investment costs, the total money savings and the payback period. Nothing is presented for the current and future energy costs which, as in the energy analysis, makes impossible to reference the savings. However, it is the only DSS that presents the "CO_2 reduction costs" and, together with *Retrofit Advisor*, the only DSSs presenting *access to finance*, which is a useful indicator in order to encourage the user to take action on retrofit.

Generation has the constraint of having a simulation of the access to finance limited to micro generation. It would be a consistent and strong analysis if applied to the retrofit project itself. Apart from that, it only presents the current and expected energy costs. *TABULA* presents a poor economic analysis as well, by only presenting the same two indicators. For these two DSSs the economic analysis is only a limited secondary analysis.

Table 12 presents the comparison of the DSSs against indicators of dimension F.

Table 12 - Comparison of the DSSs against the indicators of dimension F.

Dimension F Economic	**DSS**				
	BioRegional Tool	***Generation***	***ICE (2.0.8)***	***Retrofit Advisor (β)***	***TABULA***
F1. Current total energy costs	No	Yes	No	Yes	Yes
F2. Retrofit Budget	No	No	No	Yes	No
F3. Total investment costs	Yes	No	No	Yes	No
F4. Investment cost per retrofit measure	Yes	No	No	Yes	No
F5. CO_2 reduction costs	Yes	No	No	No	No
F6. Total money savings	Yes	No	No	No	No
F7. Money savings per retrofit measure	No	No	No	No	No
F8. Expected total energy costs	No	Yes	No	Yes	Yes
F9. Payback period	Yes	No	No	No	No
F10. Maintenance cost	No	No	No	Yes	No
F11. Access to finance	Yes	No	No	Yes	No

Each indicator is discussed in the paragraphs below.

F1. Current total energy costs

Generation, *Retrofit Advisor* and *TABULA* present this indicator. *Generation* presents additionally the current energy costs broken down by energy source.

F2. Retrofit budget

The only DSS presenting this indicator is *Retrofit Advisor*. The user is allowed to enter the amount of "own funds" (equivalent to *retrofit budget*) and the amount corresponding to the "bank loan". However, there is one limitation: the total of the two amounts must be equal to the total investment costs of the scenario plus the site value (€/m^2). The whole analysis provided by *Retrofit Advisor* is based on the property value, which means that the site value is taken into account even if it is not an available amount of money. This may represent a source of confusion to the user.

F3. Total investment costs & F4. Investment cost per retrofit measure

Only *BioRegional* and *Retrofit Advisor* have these two indicators present in their economic analysis. It was expected that they both appeared in the same DSS, since the investment cost per retrofit measure represents the underlying calculation for achieving the total investment costs. Nevertheless, in neither of the two DSSs a complete discrimination of the retrofit measures is available. The user is thus confronted with an estimate for which there is not reliable underlying data. In *BioRegional* the retrofit measures presented, for which the investment cost is shown, are referred as the ones "that were used as a basis for the calculations". However, it is still impossible to know which particular measures that led to the particular retrofit scenario. On the other hand, *Retrofit Advisor* presents the investment cost per type of retrofit measure such as envelope, extensions or technical installations works. Although a different case, the user is again confronted with less reliable and less specific data.

F5. CO_2 reduction costs

BioRegional presents this indicator associated both with the retrofit scenarios and with each retrofit measure.

F6. Total money savings

Only *BioRegional* presents the total money savings for each scenario. *Generation*, *Retrofit Advisor* and *TABULA* present both the current energy costs and the expected energy costs but they do not express clearly the difference between the two values (i.e. money savings). The inconsistence of this method is that it compels the user to do the calculations on its own which do not agree with the purpose of using a DSS.

F7. Money savings per retrofit measure

This is the only indicator from the dimension that it is absent throughout the DSSs. Like with the investment costs (see D3 & D4), it would be to expect for *BioRegional* to present this indicator because it already presented the total money savings, and the former is needed to calculate the latter. This may again represent an inconsistency in the underlying calculations.

F8. Expected total energy costs

As expected, the DSSs that presented this indicator also presented the indicator current total energy costs: *Generation*, *Retrofit Advisor* and *TABULA*. *Generation* presents also the expected total energy costs broken down by energy source.

F9. Payback period

This indicator is presented only by *BioRegional*, both for the scenarios and for the measures alone. However, the payback period for the measures alone may not have an easy interpretation and thus become an unintelligible indicator. Both *Generation* and *Retrofit Advisor* use, as an economic tool of analysis for the investment, the discounted cash flow (DCF) method instead of the payback period. In addition, *Generation* presents the payback period but only for the investment in micro generation technologies, which is an economic analysis presented separate from the analysis of the retrofit scenarios.

F10. Maintenance cost

Retrofit Advisor includes an indicator that expresses the "periodic costs" with the building, which excludes the ones related to the energy expenses. In addition to capital, administration and service and disposal costs, the indicator includes repair and maintenance costs in the annual periodic costs.

F11. Access to finance

Although in different forms, two are the DSSs that present this indicator. *BioRegional* suggests the option of Government financial support through subsidies in order to finance the measures. For every retrofit measure considered, the DSS calculates which ones are cost-effective and which ones (both cost-effective and not) are able to qualify for three different Government financial support programmes: i) Green deal, ii) Feed-in tariff payments and iii) Renewable heat incentive payments. On the other hand, *Retrofit Advisor* checks for financial institution loans to support the whole retrofit project and it presents the DCF method for the economic analysis.

Table 13 shows the total score, based on the amount of present indicators, of each DSS for the dimensions A, D, E and F.

Table 13 - Total score of each DSS for the 32 indicators.

Dimensions	**Decision Support Systems**				
	BioRegional Tool	***Generation***	***ICE (2.0.8)***	***Retrofit Advisor (β)***	***TABULA***
A	5	5	1	4	4
D	3	6	4	11	7
E	4	2	3	2	2
F	6	2	0	7	2
Total (32)	**18**	**15**	**8**	**24**	**15**

The DSS which presented the highest number of indicators suggested in this research was *Retrofit Advisor* with 24 indicators (75%) followed by *BioRegional* with 18 (56%), *Generation* and *TABULA* with 15 (47%) and finally *ICE (2.0.8)* with only 25% of the list of indicators present.

6.2.2 Comparison of the units used in the DSSs

The units used by the DSSs to express the indicators vary to a great extent when compared to the ones suggested by this research but also amongst DSSs. In 61% of the cases, the units used differ from the ones suggested. Tables 14, 15 and 15 present the comparison between the units used by the DSSs and the ones suggested in Section 6.1.1, for dimensions D, E and F, respectively.

Two main differences are observed in the three dimensions for *BioRegional* and *Generation*. The former is a DSS created in the United Kingdom and therefore the currency used is the pound instead of the euro. The intent of the developers is for the DSS to be used in different regions of the United Kingdom. *Generation* performs the two analysis based on a monthly analysis. Although for some indicators the values are also presented annually, in some cases the total values are not presented.

Table 14 - Comparison of the units used by the DSSs for dimension D.

Indicator	**Units**	**Decision Support Systems**				
		BioRegional Tool	***Generation***	***ICE (2.0.8)***	***Retrofit Advisor (β)***	***TABULA***
D1	$kWh/m^2.a$	-	kWh/a kWh/month	-	$kWh/m^2.a$	$kWh/m^2.a$
D2	$kWh/m^2.a$	kWh/a	kWh/a kWh/month	-	kWh/a	$kWh/m^2.a$
D3	$kWh/m^2.a$	kWh/a	kWh/a kWh/month	$kWh/m^2.a$ kWh/a	kWh/a	$kWh/m^2.a$
D4	Label	-	-	letter	letter	-
D5	$kWh/m^2.a$	-	-	-	%	-
D6	$kWh/m^2.a$	kWh/a	-	%	-	-
D7	$kWh/m^2.a$	-	kWh/a kWh/month	-	$kWh/m^2.a$	$kWh/m^2.a$
D8	$kWh/m^2.a$	-	kWh/a kWh/month	-	kWh/a	$kWh/m^2.a$
D9	$kWh/m^2.a$	-	kWh/a kWh/month	-	kWh/a	$kWh/m^2.a$
D10	$kWh/m^2.a$	-	-	-	-	% of needed energy
D11	Label	-	-	letter	letter	-
D12	-	-	-	-	-	-

Regarding energy indicators, the biggest difference was in their expression of the annual values per square meter of the building. Neither *BioRegional* nor *Generation* present the annual values per m^2. *Retrofit Advisor* has some inconsistency once it presents the total annual energy consumption values per m^2 while the energy consumption values broken down by energy source and end use are only presented by annum. *ICE (2.0.8)* opted by presenting the two separate values and *TABULA* was an exception since it expressed all the indicators, whether from dimensions D, E and F, per square meter and annum.

Table 15 - Comparison of the units used by the DSSs for dimension E.

Indicator	Units	Decision Support Systems				
		BioRegional Tool	*Generation*	*ICE (2.0.8)*	*Retrofit Advisor (β)*	*TABULA*
E1	kg CO_2e/ m^2.a	kg CO_2e/a	t CO_2e/month	kg CO_2e/m^2.a kgCO_2e/a	kg CO_2e/m^2.a	kg CO_2e/m^2.a
E2	kg CO_2e/ m^2.a	% of CO_2 current emissions	-	-	-	-
E3	kg CO_2e/ m^2.a	%	-	trees and cars	-	-
E4	kg CO_2e/ m^2.a	kg CO_2e/a	t CO2e/month	kg CO_2e/m^2.a	kg CO_2e/m^2.a	kg CO_2e/m^2.a

Regarding environmental indicators, some differences were observed. *Generation* uses tonnes (t) instead of kilograms (kg) of CO_2e which might be exaggerated for monthly values. *ICE (2.0.8)* chose to express CO_2 emissions in trees and cars "saved" and *BioRegional* chose to express the savings, both of energy and CO_2 emissions, in percentage of the current situation. This choice might reveal an effort to facilitate the comprehension of the indicators to the users.

Table 16 - Comparison of the units used by the DSSs for dimension F.

Indicator	Units	Decision support systems				
		BioRegional	*Generation*	*ICE (2.0.8)*	*Retrofit Advisor (β)*	*TABULA*
F1	€/a	-	€/month	-	€/a	€/m^2.a
F2	€	-	-	-	€	-
F3	€	£	-	-	€	-
F4	€	£	-	-	€/type of measure	-
F5	€/kg CO_2e	£/kg CO2 e	-	-	-	-
F6	€/a	£/a	-	-	-	-
F7	€/a	-	-	-	-	-
F8	€/a	-	€/month	-	€/a	€/m^2.a
F9	a	a	-	-	-	-
F10	€/a	-	-	-	€/a	-
F11	-	-	-	-	-	-

Considering only the present indicators in each DSS for the energy and environmental analysis dimensions, *TABULA* was the DSS that revealed more consistency in the units (67%), followed by *ICE (2.0.8)* (40%), *BioRegional* (29%), *Retrofit Advisor* (22%) and finally *Generation* without any of the units suggested (0%). Regarding economic analysis dimension, *Retrofit Advisor* matched all the units suggested, *BioRegional* only 20% and the other three DSSs did not use any of the units suggested.

6.3 Decision Support Systems Adoption

Hitherto - in this chapter- we have assessed the characteristics of each DSS versus a set of indicators selected from the literature. We have concluded they all differ to a great extent in their capabilities and that each DSS retrieves a different analysis. Whereas the previous comparison focused on a quantitative approach by assessing how the DSSs evaluate the impact of retrofit measures, the present comparison focus on a qualitative approach by assessing how the DSSs interact with its user. The goal of conducting this comparison is to assess the performance of the DSSs from the perspective of the user. The quality of that performance, through the interface DSS-user, influences the adoption and diffusion of the DSS among users. It is thus relevant to understand which characteristics of a DSS favour its adoption and hence evaluate the potential of adoption of the selected DSSs. For the dissemination of a technology, not only it is important to have standardized methods in the analysis performed but it is also equally important to have innovative characteristics. Besides being accurate in its analysis, a DSS should have relative advantage, be simple, compatible, trialable and observable. In the next sections the evaluation of these concepts will be discussed.

6.3.1 Methods

Rogers (1995) developed a model to assess the diffusion of innovation technologies. He has developed a “standard classification scheme for describing the perceived attributes of innovations in universal terms” (Rogers, 1995). The author defines five characteristics of innovations that influence the decision of the individual to adopt or reject the technology. Based on Roger’s framework, Staats (2013) applied the model to DSSs for sustainable retrofit, by developing specific parameters and benchmarks for each innovation characteristic. The author analysed the homeowner adoption of DSSs in the Netherlands in order to give insights for DSSs improvement that can accelerate sustainable refurbishment. The five attributes of innovations defined by Rogers (1995) and their application to DSSs for retrofit developed by Staats (2013) are as following:

Relative advantage represents the extent to which the innovation is perceived as being better than the tool/practice it replaces. Applied to DSSs, is regarded as the benefits and solutions the user is able to acquire from it.

Compatibility describes the coherence of the innovation with the values, experience and perceived needs of the potential users. A DSS would be more compatible if its software is available for every computer system, its interface clear and attractive and it communicates with the user in using knowledge he understands.

Complexity represents the level of difficulty experienced by the potential adopter when dealing with the innovation. If a technology is more difficult to understand or adopt, it will diffuse slower. Regarding DSS, its complexity is reflected on the number and logical description of the input and output variables and in providing clear descriptions of the functions and their sequence.

Trialability refers to the extent to which a user can try and experiment the innovation before committing to full adoption. The innovations that provide trial contribute to lower uncertainty regarding its use and enable faster adoption. This is reflected in a DSS by software availability, accessibility and by the easiness of adjustments to the inputs.

Observability is related to the ability of the adopter to actually see the innovation being used by others. If the innovation is easy to find and frequently mentioned it is more likely to be adopted. A DSS for retrofit is observable if easily found in the internet search engines and if associated with successful projects.

The development of the model for DSSs for retrofit provided by Staats (2013) was applied to the five selected DSSs for this research. However, that model intended to be applied in the Netherlands, thus it needed to be adapted to the framework of this research. In addition, the present research had already developed an extensive analysis of DSS characteristics and hence some of the parameters suggested in the model had been previously assessed. The scales of the weights and scores were also adapted. Consequently, adaptations were made to the parameters, weights and benchmarks suggested by the model in order to ensure the coherence with the goals and previous sections of the present research. The adaptations to the model were the following:

1. The scale of relative importance of the parameters was modified from a 0-4 scale to a 0-3 scale. The original scale ranged from 0 (not important at all) to 4 (very important), as described by Staats (2013). However, it was not clear the meaning of the intermediate weights, which, in our perspective, could introduce a lack of accuracy in the assignment of relative importance of the parameters. For a matter of clarity, the model was adapted to include a scale of weights from 0 to 3. Accordingly, the scale of the scores to evaluate the degree to which the DSS applies each parameter presented the same problem. The scale presented by the author ranged from 0 (not applied at all) to 4 (applied very effectively) and the meaning of intermediate scores was not presented. For the same reasons mentioned for the scale of weights, the scale of scores was adapted to a scale from 0 to 3. Table 17 shows the meaning of two scales. The weight of each parameter was adjusted to the new scale and is presented in Table 18.

Table 17 - Meaning of the scales for the scores and weights of the parameters.

Scales		
Score	**No.**	**Weight**
Not applied at all	**0**	Not important at all
Applied ineffectively	**1**	Low importance
Applied effectively	**2**	Medium importance
Applied very effectively	**3**	High importance

2. Given that in Section 6.1 the list of indicators developed enabled the comparison of the indicators used in the economic, energy and environmental analysis and also the units used to express the indicators it was not necessary to perform that comparison again. Consequently the benchmark for the sub-parameters "financial", "energetic" and "environmental" was modified in order to assess the clear presentation of the benefits in the scenario analysis retrieved, which had not yet been assessed in this research. So that the user can make an informed decision on the retrofit project to undertake, it is of major importance that its benefits are clearly expressed. The sub-parameter "health" was modified to "social" and refers to the increased comfort and living conditions.
3. The parameter "Standard Dutch inputs" suggested by Staats (2013) was considered unnecessary and was not used in the comparison.
4. Considering the relevance given in this research to the EU building energy label, the parameter suggested by Staats "Usage of EU Labels" was modified to "Usage of EU building energy label".
5. It was considered relevant to assess the presence of errors in the DSS as a "compatibility" parameter. Errors can reduce the accuracy of the analysis and give imprecise results. Furthermore, they may discourage the user in using the DSS.
6. Given the definition of the perceived attribute "compatibility", the appeal and representativeness of the name of the DSS was considered as a parameter to match the needs of the potential adopter[30]. However, as a subjective parameter, it influences the adoption of a DSS in a lesser extent than other parameters.

[30] Rogers argues that "Naming of innovations is often careless, but issues of compatibility can ruin a poorly named innovation". For more on this topic see Ellsworth (p.50, 2000).

Following the methodology used by Staats (2013), the parameters presented in Table 18 were used to analyse the adoption attributes of the five selected DSSs using a multi criteria decision analysis. By assigning weights to each parameter it is also possible to attribute different levels of importance to each parameter of the five characteristics. The relative importance of each parameter ranges from 0 (not important at all) to 3 (high importance). Each DSS is evaluated by the extent to which it applies the parameter, ranging from 0 (not applied at all) to 3 (applied very effectively). The DSS weighted scores for each parameter are obtained by multiplying the score for the weight. By summing the weighted scores of all the parameters, the total score for each DSS is obtained. According to this method, the highest scoring DSS would be the most adopter friendly on the perspective of the user. The results of the MCDA are further discussed and conclusions are drawn at the end of the chapter.

The innovation characteristics and the associated parameters, sub-parameters, weights and benchmarks with the adaptations previously[31] mentioned are presented in Table 18.

[31] The original table presented by Staats (2013) is presented in Appendix III.

Table 18 - Parameters, weights and benchmarks for each innovation characteristic.

Innovation characteristic	Parameter	Sub-parameter	Weight	Benchmark
Relative advantage	Clear information regarding options	Specific retrofit options suggested	3	Retrofit measures/scenarios appear clearly in the DSS and have clear descriptions
	Clear benefits	Financial	3	Benefits are presented clearly by scenario
		Energetic	3	Benefits are presented clearly by scenario
		Environmental	3	Benefits are presented clearly by scenario
		Social	3	Benefits (increased comfort and living conditions) are presented clearly by scenario
	Specificity of input	Detail of input requested	2	Specific amounts (kWh), approximations (10-50 kWh, 51-100 kWh, etc) or subjective groups (low, average, high)
	Possibility to run different scenarios		3	2 to 5 scenarios able to run together and be compared
Compatibility	Software	Source (Web-based, MS Excel-based, MS Windows-based software)	3	Web-based (usable with IE, Firefox and Chrome); MS Excel and MS Windows-based (easy to install and run)
		Errors	2	Absence of errors or crashes during running
	Representative name/title of DSS		1	Appealing and simple name
	Usage of EU building energy label	Input	2	Input usage of EU building energy label
		Output	2	Output usage of EU building energy label
	Interface design	Clear layout	2	Immediate comprehension of layout
		Clear navigation	2	Immediate comprehension of which indicators to fill in and how to evoke the analysis
		Attractiveness	2	Subjective description
Complexity	Complexity of input		3	Moderate amount of input variables needed
	Complexity of output		3	Moderate amount of output variables delivered
	Logical input descriptions		2	Comprehensible to all stakeholders/users
	Logical output descriptions		2	Comprehensible to all stakeholders/users
	Help function		3	Availability and profoundness of explanation/help function (simple and straightforward)

Trialability	Easiness of adjustments		1	Adjustments to the input instantly after the first simulation of scenarios
	Availability	Free/Demo version/Paid version	3	Demo version use in weeks/Price in €
Observability	Appearance on the internet	Using English keywords: "building retrofit", "energy savings", "Europe" and "software"	2	Software appearance within the first page
		Using title/name of software as keywords	1	Software appearance within the first 3 links
	Reference in real retrofit case studies	Using title/name of software and project as keywords	2	More than 3 references

6.4 Results from the comparison of adoption characteristics

The model developed by Staats (2013) was adapted to the present research and applied to the five selected DSSs. In this section the results are presented and discussed. First, the differences between the DSS are discussed by each innovation characteristic and second, the score of each DSS by parameter is presented. Finally, the main findings of the application of the model are presented.

Relative advantage

The retrofit options, both scenarios and measures, suggested by the DSSs are clearly presented and are comprehensible to the user in *BioRegional*, *ICE, Retrofit Advisor and TABULA*. *BioRegional* and *TABULA* present (predefined) scenarios clearly and explain which retrofit measures are considered for each scenario. *Retrofit Advisor* also presents predefined scenarios but the user is allowed to change the measures that make each scenario. *ICE* presents predefined scenarios for each type of measure. Although these four DSSs differ to some extent in the way of presenting scenarios and measures, they are all clear in the information retrieved. *Generation* allows the user to make different scenarios by choosing amongst predefined measures that are clearly suggested by the DSS. This option might discourage the user that it is not aware of which retrofit measures to select.

Regarding the presentation of the financial, energy and environmental benefits, *TABULA* presents them in a clear way, by scenario. *ICE* only presents energy and environmental benefits but they are also clear by each scenario. *BioRegional* gives more emphasis to the financial and environmental, being the energy benefits only presented by measure. *Generation* displays the results graphically (by month) which might confuse the user. *Retrofit Advisor* presents the three benefits by scenario, but dispersed by different excel sheets and presented among other type of information which makes the presentation less clear. Social benefits are only presented by *Retrofit Advisor* by assessing through subjective groups the importance to the user of aspects such as “architectural and cultural”, “construction quality” and “quality of living” among others.

The input requested in *BioRegional*, *ICE (2.0.8)* and *Generation* is detailed, since they all ask for specific amounts. *Retrofit Advisor* asks specific amounts although for some input variables, such as some retrofit measures and social aspects, it works with checkboxes with subjective groups. *TABULA* only asks for the selection of two typologies (building + HVAC system) which are predefined thus not allowing any modification of parameters. Because they have a lack of input detail, these two situations may compromise the accuracy of the results and therefore the DSSs score lower in the parameter.

The DSSs differ in the number of scenarios simulated: *BioRegional* runs 12 scenarios, *TABULA* runs 2, *Retrofit Advisor* runs 3 and *ICE* runs 6. More than five scenarios imply more time to understand the differences and may confuse and discourage the user. *Generation* is able to compare different scenarios but each one has to be simulated separately. This process takes longer and the user may not have the knowledge to make different scenarios.

Compatibility

TABULA is a web-based tool and is therefore very easy to access in different internet browsers. *Retrofit Advisor* and *BioRegional* are MS Excel-based software and require the file to be downloaded to the computer of the user. *Generation* and *ICE (2.0.8)* use MS Windows-based software which requires to be installed, taking some installation steps which might discourage the user. Additionally, *Generation* presents an incompatibility with different versions of MS Windows (Vista and 7) and may present errors retrieving the final report unless the regional configuration of the computer is changed[32]. This is highlighted on the "User Guide" as shown in Figure 15 (Appendix IV).

Only *Retrofit Advisor* presented errors and bugs during simulation. Since the DSS is a test-version, incompatibilities were expected. After activating macros on Microsoft (MS) Office Excel it reports that "There are not enough system resources to show everything"[33] (see Figure 16, Appendix IV). After this, the DSS is able to run. Two major problems were reported: i) advice to fill the required fields was presented in German, although English was selected at the beginning (Figure 17, Appendix IV) and ii) typologies are not refreshed when another country is selected. Only Swiss building typologies are presented.[34]

Retrofit Advisor is an appealing name and representative of the purpose of the DSS whereas from the remaining DSSs the user does not get an immediate comprehension of the DSS function. *BioRegional* is presented on its webpage by the name "Energy retrofit tool for buildings" although the name given to the software file is "BioRegional retrofitting strategy tool". Both the names are representative and appealing but the fact there are more than one name for the DSS can hinder the dissemination of the DSS. As a word, *TABULA* and *ICE* do not have any meaning. *Generation* might be associated with meanings other than building retrofit. Although with the complete name of *TABULA* and *Generation* the user may get more insight of the purpose of the tool, it is still not immediate. Through the full name of *ICE* (Informe de Conservación del Edificio y Evaluación energética) only users fluent in Spanish can understand the function of the DSS.

As expected from the analysis conducted in Section 6.2, only *ICE* and *Retrofit Advisor* make use of the EU building energy label as an additional indicator both in input and output to assess the energy performance of the building. Figures 18 and 19 (Appendix IV) give an overview of the building energy label in *Retrofit Advisor* and *ICE*, respectively.

Amongst the five DSSs, *TABULA* presents the better designed interface: it is easy to understand and navigate through it, has only 5 sections and two required input fields (building and HVAC system typologies). *BioRegional* it is also easy to understand, having 5 sections with a total of 4 input variables but the interface is less attractive than the one from TABULA because it is an MS Excel-based software. *ICE* has a complex interface with 13 tabs and several sub-tabs each that contain many input variables and checkboxes. Although navigation is apparently clear, the great amount of input makes the layout difficult to understand and follow. *Generation* is organized in 2 menus with several sub-menus that contain less input variables and checkboxes when compared to *ICE*. Layout is better but navigation is less intelligible due to an extensive characterization of the building with many technical parameters which are not readily understood. Finally, *Retrofit Advisor* is the worst designed

[32] Nevertheless, the incompatibility was not observed during the test of the present research with MS Windows Vista.

[33] The DSS was ran in several computers and always presented the error.

[34] Yet, when selecting another country the currency changes from Swiss Franc (CHF) to Euro (€).

interface. Layout is confusing due to the large amount of input (that is repeated for the actual situation and for the 3 retrofit scenarios) and the use of several different colours. Navigation is almost unintelligible for three main reasons: i) because the DSS uses typologies but allows manual input, every input is already filled in, ii) it is difficult to understand the input and output sequence in the excel-sheet sequence and iii) some results are presented among the input sequence. An overview of the work environment of each DSS is presented from Figure 20 to 24 in Appendix IV.

Complexity

The "complexity" of the variables differs between the input and output. As already mentioned in the analysis of the "compatibility" of the tools, while *Generation*, *ICE* and *Retrofit Advisor* require a large amount of input variables (more than 50), *BioRegional* and *TABULA* only require 4 and 2 input variables, respectively, to perform the analysis, being less complex. The "complexity" of the output differs to a lesser extent: *BioRegional* presents 13 output variables, *Retrofit Advisor* 17, *Generation* 15, *ICE* 12 and *TABULA* 10. Examples of the amount of input and output variables of each DSS are presented from Figure 25 to 34 of Appendix IV.

As for the descriptions of the input, *Generation*, *ICE (2.0.8)* and *Retrofit Advisor* use a high number of technical terms which are complex to users without any technical background on buildings. *BioRegional* and *TABULA* are much easier since the first only asks the building typology and data on energy consumption and the second only asks the user to choose typologies which than contain all the technical parameters. As expected, the descriptions of the output are easier to understand than the input. Still, they all present some output variables that are not of immediate comprehension such as the "energy demand" or the "primary energy consumption". Exception made for *Retrofit Advisor* that scored the lowest because it displays financial indicators that are unintelligible for the majority of the users such as the "return on capital (%)" or the "capital distribution" between outstanding bank loans, actual own funds and increase on own funds.

The DSSs differ to a great extent in the form and content of the "help function". *BioRegional* explains the navigation of the DSS and the input and output in the first and second tabs. The explanation is simple and straightforward and helps the user using the DSS (Figure 35, Appendix IV). *Generation* does not provide any explanation in the work environment. Nevertheless it provides a complete and comprehensive, although long, user guide (98 pp.) that is downloadable separately (Figure 36, Appendix IV). Since without the user guide it is very complex to understand how to work with the DSS, this might discourage the potential adopter. *ICE* provides a drop-down menu named "help" that links to the "user guide" (231 pp.) but also to 10 different and shorter documents explaining each tab (Figure 37, Appendix IV). The documents are confusing and contain equally technical information. *TABULA* provides a link that opens a "user guide" (10 pp.), explaining the work environment of the DSS, which is straightforward (Figure 39, Appendix IV). Finally, *Retrofit Advisor* provides helpful explanation of several input variables by pop-up boxes near the input. However, it does not provide help for every complex variable and the help on the navigation of the DSS (that appears in the first tab) could be clearer (Figure 38, Appendix IV).

Trialability

BioRegional, *Retrofit Advisor* and *TABULA* allow immediate adjustments of the input after the first simulation. *Generation* and *ICE (2.0.8)* are less trialable. They allow the adaptation of input variables but they require some minutes to simulate the new scenario.

As discussed in chapter 5, the selected DSSs for this research are all free software. Thus, all the DSSs scored high on the availability of the software.

Observability

As expected, the DSSs were more difficult to find on the internet when using keywords such as "building retrofit" and "energy savings" then when using the title of the software. When using keywords on the search engine only *BioRegional* and *Retrofit Advisor* appeared and only when using a combination of two keywords. When searching by the title of the DSS only *BioRegional* and *Retrofit Advisor* were found immediately. *ICE (2.0.8)*, *TABULA* and *Generation* only appeared when using the full name of the DSS on the search engine. Unexpectedly, only three DSSs were referenced in the literature concerning real retrofit case studies: *BioRegional*, *TABULA* and *Retrofit Advisor* with one reference each.

The scores for each DSS can be found in Table 19.

Table 19 - Score of each DSS by parameter.

Innovation characteristic	Parameter	Sub-parameter	BioRegional Score	Generation Score	ICE (2.0.8) Score	Retrofit Advisor Score	TABULA Score	Weight
Relative advantage	Clear information regarding options	Specific retrofit options suggested	3	2	3	3	3	3
	Clear benefits	Financial	3	2	0	2	3	3
		Energetic	2	2	3	2	3	3
		Environmental	3	2	3	2	3	3
		Social	0	0	0	2	0	3
	Specificity of input	Detail of input requested	3	3	3	2	2	2
	Possibility to run different scenarios		2	1	2	3	3	3
Compatibility	Software	Source (Web-based, MS Excel-based, MS Windows-based software)	3	1	2	3	3	3
		Errors	3	3	3	1	3	2
	Representative name/title of DSS		2	1	1	3	1	1
	Usage of EU building energy label	Input	0	0	3	3	0	2
		Output	0	0	3	3	0	2
	Interface design	Clear layout	3	2	1	1	3	2
		Clear navigation	3	1	2	1	3	2
		Attractiveness	2	2	2	1	3	2

			BioRegional	**Generation**	**ICE (2.0.8)**	**Retrofit Advisor**	**TABULA**	Weight
Innovation characteristic	**Parameter**	**Sub-parameter**	Score	Score	Score	Score	Score	
Complexity	Complexity of input		3	1	1	1	3	3
	Complexity of output		2	2	2	2	2	3
	Logical input descriptions		3	1	1	2	3	2
	Logical output descriptions		2	2	2	1	2	2
	Possibility of explanation/Help function		3	1	1	2	3	3
Trialability	Easiness of adjustments		3	2	2	3	3	1
	Availability	Free/Demo version/Paid version	3	3	3	3	3	3
Observability	Appearance on the internet	Using English keywords: "building retrofit", "energy savings", "Europe" and "software"	2	0	0	2	0	2
		Using title/name of software as keywords	3	0	2	3	2	1
	Reference in real retrofit case studies	Using title/name of software and project as keywords	1	0	0	1	1	2

The outcome of the MCDA can be found in Table 20. The table also shows the benchmark for each characteristic. The previous comparison enabled the evaluation of the performance of the DSSs from the perspective of the user and evaluation of their potential of adoption and diffusion among users. Through the results of the MCDA analysis we found that *TABULA* and *BioRegional* are the highest scoring DSSs, presenting the same final score. *Retrofit Advisor* ranks in third place followed by *ICE (2.0.8)* and *Generation*.

Table 20 - Final results of the Multi Criteria Decision Analysis.

	BioRegional	***Generation***	***ICE (2.0.8)***	***Retrofit Advisor***	***TABULA***	**Benchmark**
Relative advantage	45	33	39	46	49	80
Compatibility	33	20	35	32	34	64
Complexity	34	18	18	21	34	52
Trialability	12	11	11	12	12	16
Observability	9	0	2	9	4	20
Total	**133**	**82**	**105**	**120**	**133**	**232**

The highest scoring DSSs (*TABULA* and *BioRegional*) differ 50 points from the lowest scoring DSS (*Generation*), which reveals a significant difference between the adoption potential of the selected DSSs. As expected, the most "technical" DSSs, *ICE* and *Generation*, are the ones that perform poorly and have therefore, less potential for being adopted. The diffusion of these two DSSs is hindered due to their complexity in the number and description of the input and output, the long and exhaustive help function, the difficulty in adjusting the scenarios after simulation and the lack of clear information and benefits to the user. They also stand out amongst the other DSSs due to their poor "observability", since they are difficult to find in search engines and there are no references that link those DSSs with real retrofit cases. *BioRegional* and *TABULA* present the same total score although they differ in some characteristics. They are the less complex DSSs, present a clear and attractive interface and are clear in retrieving the scenarios and their benefits. The biggest difference is on "relative advantage" in which *BioRegional* scores lower due to the exaggerate number of scenarios simulated automatically (12) and the lack of energy benefits per scenario and on "observability" in which *TABULA* scores lower than *BioRegional* due to its poor appearance on the internet. Finally, *Retrofit Advisor* scores a little lower than *BioRegional* and *TABULA* due to its lower "compatibility" and bigger "complexity". Maybe due to the fact that it is the only DSS that is a test-version, it presents the worst interface design and it is the only DSS that presents software errors. Furthermore it is the more complex on the logical descriptions of the output.

It is also relevant to notice that even the highest scoring DSSs, *BioRegional* and *TABULA*, are still distant from the benchmark DSS, the one that would score the maximum number of points (232). In a general way, this means that all the DSSs should improve their characteristics in order to meet the needs of the users and diffuse faster amongst them. Although strongly for *Generation*, *ICE (2.0.8)* and *Retrofit Advisor*, they all should decrease their "complexity" so that the users can follow the simulation and reach a solution they understand. "Compatibility" is also a characteristic that should be improved with special focus on the software source and on the interface design. The fact that all the DSSs are relatively high scored in "relative advantage" might be a proof that these DSSs are fulfilling a need from the users that intend to retrofit their buildings. However, improving this characteristic would accelerate diffusion and enhance the feeling that the DSS is useful and that it is possible to achieve clear information and benefits by its use. Finally, all the characteristics, especially "trialability", are disabled if the DSS is not observable. If the user is not able to find a DSS for retrofit he will feel less encouraged to improve the energy efficiency of his building. *Generation* and *ICE* should focus on making the DSSs observable to the users so they can try them. *BioRegional*, *Retrofit*

Advisor and *TABULA* should focus on using the DSS in more real case studies and improve the appearance on the internet search engines.

6.5 Summary and Conclusions

In the present chapter, two different comparisons of the selected DSSs were developed. The first intended to evaluate and compare how the DSSs assessed the impact of retrofit measures on buildings and the second to evaluate and compare how the DSSs interact with the user.

To perform the first comparison, the selected DSSs were compared against the list of indicators developed for this research in order to assess how they evaluate the impact of retrofit measures in a building (see 6.2.1). The indicators were developed from six general dimensions: i) technical, ii) input, iii) output, iv) energy, v) environmental and vi) economic. Through these dimensions it was possible to evaluate how the DSSs gathered information about the building and evaluated its energy performance, which retrofit measures were considered, how they retrieved information about the retrofit scenarios and finally, how consistent were their energy, environmental and economic analyses of the impact of the retrofit measures.

Throughout the DSSs it was observed that both the energy and environmental analysis were more complete and extensive than the economic analysis. The economic analysis was in general poor and secondary in most of the DSSs. The units used to express the indicators varied to a great extent and in 61% of the cases were different from the ones suggested by the present research. *TABULA* was the best scored DSS in the compliance with the units suggested. In general, it was noted that the practices in DSSs for retrofitting are far from being standardized. The DSSs were extremely varied in the analyses they provided and in the organization of the interface. The best scored DSS was *Retrofit Advisor* with 75% of the indicators suggested (24 out of 32 indicators). It was the best scored DSS in both energy and economic dimensions. It was followed by *BioRegional* with 56% of the indicators, *TABULA* and *Generation* with 47% and *ICE (2.0.8)* with only 25%. *ICE (2.0.8)* did not present economic analysis. No single DSS presented all of the desirable indicators. Nevertheless, the fact that *Retrofit Advisor* presented 75% of the indicators suggests it is possible to integrate, at least, the majority of indicators.

The second comparison was performed by using the model developed by Staats (2013) to assess the diffusion of DSSs for sustainable retrofit. The model was adapted to the present research and applied to the selected DSSs (see 6.4). The application of this model made possible to evaluate the innovation characteristics of each DSS, draw conclusions on their adoption potential and give advice to improve their diffusion amongst users.

It was observed that the DSSs revealed a significant difference in the results of the MCDA. *TABULA* and *BioRegional* drew in the comparison, with 133 points each. They were followed by *Retrofit Advisor* with 120, *ICE* with 105 and *Generation* with 82 points. Furthermore, all the DSSs are relatively far from the benchmark (232 points). In general, all the DSSs should try to improve their characteristics to improve the quality of interaction with the user and their diffusion amongst users. As they exist now, they are hardly observable to the users, besides being complex and difficult to use DSSs. Interface design and software source should be regarded as priorities to improve in the DSSs, followed by decreasing the complexity on the input and output, improving the clarity of the retrieved information and benefits of the retrofit scenarios, improve their ability to be found on the internet and be associated with successful projects. The fact that the DSSs are used in the design of real retrofits may increase the confidence of the user to adopt the DSS and is therefore a characteristic important to improve. Although many improvements are needed, the DSSs seem to fulfil a need of the users and present good “relative advantage”. In addition they all score high in “trialability” which reflects ability for enhancing faster adoption.

When evaluating the results of the two comparisons together we found that the DSSs differ to some extent in the two comparisons. *BioRegional* appears to be the DSS with more desirable characteristics, both in general dimensions (2nd) and from the perspective of the user (1st). *TABULA* ranks 1st from the perspective of the user although in the comparison of general dimensions it ranks 3rd. The DSS is user friendly, presents a good software source and the best interface design, although needs to improve its environmental and economic analysis. Although *Retrofit Advisor* is the DSS with the most complete general dimensions, it needs a great improvement on the innovation characteristics. Finally, *ICE (2.0.8)* and *Generation* score low in both comparisons and are the DSSs that need a bigger improvement.

7. Conclusions and recommendations for further research

In this research we have compared five Decision Support Systems for energy efficient retrofitting. Chapter 1 presents the introduction on the research theme. Chapter 2 characterizes the European building stock, discusses its energy consumption and its urgent need for retrofitting. Chapter 3 discusses the concept of energy efficient retrofitting and Chapter 4 the role of DSSs applied to retrofit. The selection of the five DSSs for retrofit compared in this research is explained in Chapter 5 and the comparative research is developed in Chapter 6. The present chapter outlines the main conclusions of this research, highlights the contribution of this work to the building retrofit domain, discusses the limitations of this study and gives advice on further research on the field.

7.1 Conclusions

The aim of this research was to assess the energy efficient retrofit process through the analysis of five DSSs for retrofit. In order to do that, a series of research questions were formulated to answer the main research question of "how can a DSS support energy efficient retrofitting measures in Europe?".

The first research sub-question was to identify the important energy efficient retrofit measures in a building. In order to answer this question an extensive literature review on energy efficient retrofit measures was done. We have concluded that the best strategy for any retrofit project is to focus the intervention first on reducing the energy demand of the building and second on transforming the energy supply towards an efficient and low or zero carbon supply. On the energy demand side the relevant retrofit measures encompass the building fabrics insulation and the reduction of air leakage on the building elements in order to reduce the heat flow, the retrofit of the building services (HVAC and DHW systems), the upgrade of lighting, equipment and appliances and finally, the installation of energy management tools to monitor the energy performance of the retrofitted building. On the energy supply side the relevant measures are the selection of the most efficient and low-carbon energy sources, the on-site production of renewable energy, the retrofit of the electrical system in order to maximize its potential and efficiency and the introduction of thermal storage to balance the intermittent production from renewable energies.

The second sub-question was "how to evaluate the impact of the previously identified retrofit measures on buildings". The answer to this question involved a two-step approach. First, the DSSs needed to be selected and second, two comparisons were performed.

During the selection of the DSSs for comparison it was observed a high number of DSSs developed (both private and free-software) but also an equally large number of DSSs in development which reveals on the one hand, a dynamic research area and on the other, a growing market. It was interesting to note that in most cases, the private DSSs were more likely developed by private companies working on building construction and retrofit domains and the free software DSSs were more likely to be developed by leading research Institutions. Likewise, the private software was targeted for other companies working in the building domain and the free software was targeted for public users in general. The two major institutions actively involved in the development of free software DSSs were IEA and EC through specific research programmes to improve building sustainability. This is an indicator of the global acknowledgment of the urgency of retrofit the building stock and of the effort in finding solutions to deal with the problem. Most of all is the acknowledgment that a DSS for retrofit can be a helpful tool to address the decision making process of building retrofit.

The DSSs varied in the software support, from MS Excel-based software to web-based and MS Windows-based software. The language options in the DSSs appeared to be directly dependent on the project scope in which they were developed and in most of the cases included also the English language. The DSSs were differentiated for the type of building stock assessed, being essentially divided into DSSs for residential buildings and for non-residential buildings, whereas the latter is further divided into DSSs for office buildings, schools, hotels, etc. The extent of the geographic locations assessed was also different: from DSSs that assessed a municipality, to DSSs that assessed regions of Europe or just random countries. Unexpectedly, the calculation of the energy label was only verified in two of the collected DSSs. Exception made to one of the eight DSSs, they all were developed or upgraded in the period 2011-2012 and thus, they should have included the calculation of the energy label. One explanation might be that the concept of the energy label has not yet been widely disseminated to the general public. This reveals an important advice for policy makers about the diffusion of the energy label. From the variety of DSSs found we can conclude that there are no standardized methods in European DSSs for retrofit and that the research efforts are not equally distributed by European regions. The North & West region appeared more actively involved than the Central & East and the South region. This difference might be linked to the fact that the share of old buildings (see Chapter 2) in the North & West is bigger than in the other regions and that the colder climate accelerate efforts to increase building comfort.

The conducted comparison of general dimensions was based on a list of indicators developed for this study (see Section 6.1.1). The six general dimensions compared were: i) technical, ii) input, iii) output, iv) energy analysis, v) environmental analysis and vi) economic analysis. From this comparison, we have concluded that the five DSSs differ to a great extent in their capabilities and that each DSS retrieves a different analysis. In general, they all presented a good technical dimension and considered retrofit measures on the building envelope, HVAC and DHW systems and micro generation. The exception is ICE (2.0.8) that only focus on an extensive analysis of the retrofit measures applied the building envelope. Unexpectedly, only BioRegional and Generation considered lighting, which is a significant retrofit measure. Regarding the input dimension, the comparison allowed us to conclude that working with building typologies (*BioRegional*, *Retrofit Advisor* and *TABULA*) appears to simplify the analysis instead of using manual input (*Generation* and *ICE (2.0.8)*). The manual input presents two problems: it is an extensive and time-consuming process and requires detailed information on the building design, fabrics and equipment which the average user is unlikely to know. On the other hand, typologies focus on generalizing characteristics for a large number of buildings which result in some lack of accuracy. What appears to be the more suitable approach is to combine the typology with manual input data, as is the case with *Retrofit Advisor*. That would save time to the user and simplify the input, but would still guarantee that relevant data such as the energy consumption is adapted to the real situation. The same issue was observed regarding the scenarios. Only *Retrofit Advisor* allowed changing parameters of the predefined retrofit scenarios. Again, it simplifies and accelerates the iterative process and gives priority to the goals and targets of the user. Manual scenarios are not advised since the identification of scenarios is part of the iterative process of a DSS and the goal of using these tools. Regarding the analysis of the impact of retrofit measures, the energy and environmental analysis were more complete and extensive than the economic analysis that was secondary in most of the DSSs. The units of the indicators were, in most cases, different from the ones suggested by this research which reveals to some extent a lack of agreement with the standard units used in the literature. Although none of the five DSSs presented all the suggested indicators, in general they complied with the list of indicators. The fact that *Retrofit Advisor* presented 75% of the suggested indicators and that only one (*money savings per retrofit measure*) of the 32 indicators was not included in any of the DSSs reveals that the suggested list gathers relevant indicators for a baseline performance of a DSS for building retrofit.

Regarding the comparison of the adoption potential of the DSSs, the five tools presented a significant difference between each other but also from the benchmark (total maximum possible score) which is the most adoptable DSS. Regarding "relative advantage", *BioRegional* and *ICE* present an exaggerate number of scenarios which hampers comparison and may confuse the user. *Generation* has manual scenarios which might discourage the user that it is not aware of which retrofit measures to select. *Retrofit Advisor* and *TABULA* should improve the detail of input asked in order to improve the accuracy of the analysis. All the DSSs are effective in retrieving solutions to the user although the presentation of the energy, environmental and economic benefits of the scenario should be improved because in some cases the user does not get a clear and immediate comprehension of the benefits. Furthermore, only *Retrofit Advisor* presents social benefits of the retrofit scenario. Regarding "compatibility", *Retrofit Advisor* has the most appealing name amongst the DSSs which can help in the diffusion amongst users. We found that, exception made to *BioRegional* and *TABULA*, the DSSs have poor interface designing, resulting in a disorganized and confusing layout that hampers the navigation through the DSS.

On the "complexity" attribute we found that while *Generation*, *ICE* and *Retrofit Advisor* require more than 50 input variables, *BioRegional* and *TABULA* require less than 5. The number of output variables is more homogeneous, varying between 10 and 17. These numbers suggests that the accuracy in the results of the DSSs might vary to a great extent. Nevertheless, a high number of input variables may discourage the user by asking for information that he is not aware of. The complex logical description of the input and output variables suggests that *ICE* and *Generation* are targeted for users that are expert on the building domain, while the remaining DSSs seem targeted for a comprehensive range of users. The help function also reflects this: *TABULA* and *BioRegional* have straightforward advice on the use of the tools, while *Generation* and *ICE* present long and complex user guides. *Retrofit Advisor* does not give clear help on the navigation of the DSS and the explanation of the input variables by pop-up boxes near the input is only presented in German due to a bug. Regarding "trialability", all the DSSs allow adjustments to the input instantly after the first simulation of scenarios, which is a helpful characteristic. Finally, except for *BioRegional* and *Retrofit Advisor*, the DSSs were generally poor on "observability" which suggests they are not capable of reaching the users and thus, less likely to be adopted and diffuse amongst users. All in all, the five DSSs fulfil a need from the users and they are capable of retrieving solutions but as they exist now, they are difficult to reach the users and if they do, issues of "compatibility" and "complexity" might probably discourage the user of using the DSS.

Considering all the conclusions made about the characteristics of the DSSs, we are able to advise some improvements for a more adequate and standardized DSS:

- Consider retrofit measures for reducing the energy demand by retrofitting the building envelope, HVAC and DHW systems and lighting. On the other hand, consider to act on the energy supply through the implementation of micro generation (see Chapter 3).
- Provide the results of the current situation and the future scenario of the building in the energy, environmental and economic dimensions and compare the relative improvement by presenting the savings.
- Improve the economic analysis by calculating the current energy costs, the future energy costs of the retrofit scenario and the savings resulting from the implementation of each measure and scenario. It is also of paramount importance to present the total investment costs with the retrofit project, compare it to the retrofit budget of the user and if needed, provide suggestions so that the user can finance the project (e.g. Government financial support). By adding the investment costs by measure it allows the user a better comprehension of the contribution of each measure. In order to compare the different scenarios and their cost-effectiveness, the simple payback period is suggested for being an easy to apply and understand method. Finally, the DSS should estimate the maintenance cost of each scenario, so the user is aware of the costs during the post-retrofit phase.
- Include the calculation of the social impacts of the retrofit scenarios through factors such as behavioural changes, comfort (thermal, visual and acoustic), indoor air quality, building accessibility and security.
- Provide the total values for energy consumption but also those values broken down by *end use* and by *energy source*. These values enable a comprehensive analysis of the type of energy being used and of the consumers of that energy and thus enhance an accurate retrofit strategy.
- Calculate the European energy label for the situation before and after retrofit. It is a fundamental tool that raises awareness of the building energy performance and allows benchmarking.
- Standardize the units of the indicators with the ones used in the literature in order to enhance benchmarking.
- Use building typologies but allow manual input to change some parameters. As building typologies tend to generalize, some parameters may not correspond to the current situation. Allowing the user to "update" the most relevant input variables would improve the accuracy

of the results. On the other hand, this function would also avoid overloading the user with input fields that he is not aware. To be modified by the user we suggest parameters such as the energy consumption data, the characteristics of the HVAC and DHW systems or the occupation profile.

- Use predefined scenarios but allow changes to the parameters to adjust the scenarios to the targets and goals of the user. The user should be able to repeat the simulation of a particular scenario with modifications such as include/remove a retrofit measure or increase/decrease the retrofit budget. This function would allow quick adjustments to the simulation thus enhancing the iterative process to reach the more suitable solution.
- The scenarios should be able to run together and allow comparison and should not exceed five so that comparison and variables do not discourage and confuse the user.
- Retrieve a summarized report of the scenarios with all the technical parameters of the retrofit measures along with the impact analysis (energy, environmental, economic).
- Reduce the number of input to the strictly necessary and avoid overloading the user with many fields of input variables. Avoid input fields with subjective groups (e.g. low) or approximations (e.g. 10-50 kWh). Specific amounts are preferred in order to enhance accurate results, unless the input is purely qualitative (e.g. yes or no).
- The output should contain graphic results to enhance quick and straightforward comparison but also the specific values of current and future situation. To facilitate comprehension it should present the analysis of the economic, environmental, energy and social impacts differentiated in such a way that are easily identified and consulted. The description of each retrofit scenario should also appear on the output.
- Improve interface design by presenting clear and organized fields with moderate text and colours. Avoid presenting input and output parameters in the same segment and presenting a high amount of input (or output) in the same tab. MS Excel-based software is not advised since the presence of the MS Excel functions on the header and the columns on the sheet make the interface unpleasant and confusing. By improving the layout of the DSS the user is involved and a more systemic approach is enhanced.
- The presence of an effective help function is indispensable and should not be overlooked. Available explanation on the different input and output fields appears to be more effective than a “user guide” which can be long, time-consuming and has to be consulted out of the DSS. Quick tips appearing near the input and output fields (e.g. pop-up boxes) would be straightforward and reduce the complexity of the terminology used. In addition, explanation of the steps of the navigation sequence at the beginning of the simulation and during the different steps would enhance a smooth experience with the tool.
- Improve the appearance on the internet search engines by disseminating the DSS in work groups, databases, newspapers, magazines and specialized publications of the retrofit and innovative technologies domain. Presentations, conferences and workshops for decision makers can be effective to diffuse the DSS. Furthermore, enhancing the contact with Universities and research centres can enable the use of the DSS in real retrofit case studies. An appealing name can also improve and accelerate diffusion amongst users on the internet.
- Update the DSS regularly in order to include new schemes of access to finance, new building energy efficiency regulations, retrofit technology updates, eliminate errors/bugs and avoid compatibility issues with new operating systems.

Standardization of practices in the DSSs for retrofit would accelerate common solutions in Europe. Europe is a heterogeneous region with many different characteristics. Probably the most important is that it encompasses different climatic regions which results in different building characteristics and thus, different strategies when planning a retrofit. Therefore, a DSS should be available for each country or at least, a DSS for each climatic region (e.g. South of Europe). In addition, we have concluded that working with building typologies would facilitate the retrofit process to a large extent.

The work of creating typologies should have to be done on a country basis and would require access to extensive statistical data. By assuring that this work is performed using common methods, we facilitate the development and comparison of retrofit strategies for the building stock. It would then be easier to create DSSs that could access those databases, based on standardized methods. This would facilitate a common language amongst the decision makers and enable benchmarking throughout Europe.

7.2 Limitations of the study and recommendations for further research

The present research was focused on energy efficient retrofit as a step towards sustainable buildings. This means that the main concern was the energy use of the building although economic and environmental impacts linked to the reduction of the energy use were also considered. However, the social impact of retrofit measures was not assessed. Social impact might be addressed by indicators such as behavioural changes, comfort (thermal, visual and acoustic), indoor air quality, building accessibility and security. Given that the social element is fundamental to reach sustainability, it is suggested to assess these impacts in a future comparative research of DSSs. Also the reduction of water use[35] and the sustainability of the materials used in the retrofit (e.g. embodied energy) were not considered throughout the comparative research of the DSSs. Due to their importance in order to reach a full sustainability of our cities and buildings, it is also suggested to take into account these two impacts in future comparisons.

Due to time restrictions we focused on the five DSSs that better framed the aims of this research. It would be interesting to compare a higher number of available DSSs to get insights on new developments and draw more comprehensive conclusions on the field of DSSs for retrofit. Furthermore, this research focused on free-software DSSs and it would be relevant to do the same comparison with private owned software DSSs. Those DSSs are targeted for a group of specific users (decision makers) who effectively work in retrofits and therefore the tools might include different characteristics in the DSSs (e.g. level of customization and detail). Performing that comparison would give relevant information concerning the main differences between free and private software.

The comparative research of the DSSs revealed two limitations. First, to address the comparison of general dimensions the input used to test the performance of the DSSs was different in each one of them. To test *BioRegional* and *ICE (2.0.8)* the predefined example of the DSSs was used, to test *Generation* the example given in the user guide was used and to test *Retrofit Advisor* and *TABULA*, a random typology was chosen. This might have led to some inaccuracy in the comparison hence the output data generated by different input data is not exactly comparable. However, the comparison of general dimensions was to discuss characteristics and capabilities of the DSSs instead of calculation methods and accuracy in the results. Second, the fact that each of the five DSSs assessed different regions of Europe and the fact that some of them worked with typologies and some with manual data could have hamper a comparison with the same initial data. However, for further research, we advice to use data from the same exact building (energy consumption, fabrics, architecture) in similar regions (e.g. South of Europe) and compare the retrofit project suggested by each DSSs. That study would generate relevant conclusions regarding the calculation methods of each DSS.

The list of indicators developed to compare general dimensions of the DSSs intended to contribute to a generic method of comparison of features in a DSS. However, because this cannot be interpreted as the *definitive* list, it is fundamental to acknowledge two cases that might occur: i) other indicators which do not came up with the present research that might appear to be equally essential to the decision making process and ii) other secondary indicators that might have relevance to other purposes but which will not change the overall outcome of the decision making process (e.g. to enhance the interface experience of the user). Furthermore, we acknowledge that the suggested list did

[35] An example of its importance is that *ICE (2.0.8)* considered the reduction of water use in the retrofit design.

not reflect comprehensively the goals and targets of the user. The retrofit budget was perhaps the only indicator of the list suggested that reflected that factor.

The comparison of the adoption potential of the DSS revealed the limitation of not testing the software amongst different types of users besides the author of the present research. It would be relevant to test the DSSs amongst different users such as house owners, housing institutions, credit institutions, building energy engineers, architects or policy makers. It would more representative of the decision makers involved in building retrofit in the design phase, would give valuable insights on the needs of the users and generate significant advice to improve the tools.

We advise future research regarding the number of input variables. A literature review would make possible to understand if there is a minimum number of input variables that guarantees the accuracy of the analysis. The test of the software amongst users would enable the selection of a range of values of input variables for which the user is not discouraged to use the DSS. The analysis of these two studies would enhance the selection of a reasonable range of values for the input variables that the DSSs should comply with in order to assure the accuracy of the analysis and encourage the user to adopt the DSS.

Finally, this research was focused on residential buildings not only because they represent the most significant share of energy consumption within the building sector but also because they present a smoother variation in building type, which makes the creation of typologies easier to develop and assess. Non-residential building stock differs to a great extent from the residential stock in occupation and energy consumption patterns, architecture, construction, among others. In addition, since 1990 that non-residential building stock presents not only the higher growth rate in energy consumption but also the highest energy use per square meter (see chapter 2). Considering that this trend is expected to grow over the next years, this share of the building stock should be the target of future researches that could focus on DSSs for retrofit non-residential buildings[36].

7.3 Final remarks

Throughout this research we have argued that the European building stock is in great need of retrofitting and that it is also the sector that holds the greatest potential for energy savings (see Chapter 2). The European ambitious goals for 2020 and 2050 to mitigate climate change and improve energy efficiency (see Chapter 1) will require a major effort to retrofit the entire building stock in the forthcoming years. Decision Support Systems will play a fundamental role in the decision making process of retrofit by ensuring a quicker and better design process. Standardized methods for retrofitting the European building stock in addition to the generalized use of DSSs can contribute to accelerate the rate at which buildings are energy efficiently renovated. Although a recent research field, there are already many DSSs for retrofit available. This shows the field is developing rapidly. During the period in which this research was developed, several DSSs in development were found.

This research intended to give a relevant contribute on the role of DSSs in supporting energy efficient retrofit by performing a comparison on five existent DSSs. We developed a list of indicators that can work as a baseline comparison for the retrofit decision making process amongst any other DSS. The suggestions given to improve the existent DSSs can also be applied as good practices for future DSSs. The underlying idea is that the standardization of indicators and methodologies used in DSS analysis can improve the decision making process. As DSSs will become more common and widespread, we expect to have contributed to a more comprehensive understanding of the state-of-the-art of DSSs for retrofit and to have highlighted the fundamental improvements that are needed to the five compared DSSs. Unlike energy simulation programs that are in development for decades and are of standard use nowadays, DSSs for retrofit are still in great development and need intensive research. We support that a free-software condition would make a DSS to spread more easily, quickly, and widely, reaching

[36] Throughout this research many DSSs for retrofitting non-residential buildings were found to be available.

a wider range of stakeholders. At a moment that it is fundamental to improve the rate of building retrofit, free-software DSSs could play an important role in knowledge diffusion and in raising awareness of the decision makers. Finally, we hope the present research has contributed to the established European goals to improve energy efficiency, mitigate climate change and build sustainable cities.

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Appendix I. Collected data from the literature review

A literature review was made in order to find the most common terms used to express the "works required to upgrade the energy and environmental performance of an aged or deteriorated building". The searched terms throughout the literature were: retrofit, refurbish, renovate, upgrade, renewal, repair, restore, modernise, convert and rehabilitate. Throughout the review, also the expressions revitalise, remodel, restructure, adapt and redevelop were found to express the works mentioned. These last terms were observed less than five times each in a world of 144 reviewed documents and, for that reason, they are not presented here.

In Table 21 of the present appendix the collected data for the ten mentioned terms is presented by type of literature. In the cases where the author(s) provide definitions of the terms used they are transcribed, after the presentation of the collected data. It was found that the terms retrofit, refurbish and renovate are by far the most commonly used in the literature and are, in 30% of the cases, used interchangeably throughout the text. From those three terms, retrofit is the most used word, followed by renovate and refurbish.

Table 21 - Frequency of used terms to express the "works required to improve the energy and environmental performance of an aged or deteriorated building".

Type of document	Authors	Words									
		Retrofit	**Refurbish**	**Renovate**	**Upgrade**	**Renewal**	**Repair**	**Restore**	**Modernise**	**Convert**	**Rehabilitate**
Articles	Diakaki et al.	×		×							
	Chwieduk, D.		×								
	Xing et al.		×								
	Mata et al.	×									
	Zhai et al.[1]	×		×							
	Silva et al.	×									x
	Power, A.		×	×	×	×	×	×	x		
	Beccali et al.	×									
	Tuominen et al.	×		×							
	Cohen et al.	×									
	Ma et al.[2]	×	×	×							
	Konstantinou, & Knaack	×	×	×							
	Ahern et al.[3]	×	x		×						
	Sodagar, B.		×							x	
	Sitar, & Krajnc			×		×					
	Hinnells, M.		×								
	Thuvander et al.[4]			×							
	Ouyang et al.	×									
	Verbeeck, & Hens	×									
	Menassa, C.[5]	×									
	Kumbaroğlu, & Madlener	×									
	Goldman, C.	×									
	Rysanek, & Choudhary[6]	×									
	Haapio, & Viitaniemi		×								
	Häkkinen, & Belloni		×	×							
	Huang, & Hsueh[7]		×								

Type of document	Authors	Words									
		Retrofit	Refurbish	Renovate	Upgrade	Renewal	Repair	Restore	Modernise	Convert	Rehabilitate
Articles	Vergragt, & Brown	x		x	x						
	Dascalaki et al.		x	x					x		
	Dascalaki, & Balaras[8]	x	x	x						x	x
	Dong et al.	x		x							
	Chidiac et al.	x									
	Dowson et al.	x	x		x						
	Xu et al.	x									
	Alanne, K.[9]	x	x	x							
	Petersdorff et al.	x		x							
	Erhorn et al.	x									
	Juan et al.[10]		x		x		x	x			
	Doukas et al.	x		x							
	Flourentzou, & Roulet[11]	x	x								
	Flourentzos, Droutsa & Wittchen	x	x	x							
	Kolokotsa et al.[12]	x	x	x							
	Leeuwen et al.		x								
	Mickaitytė et al.	x	x	x							
	Asadi et al.	x									
	Kaklauskas et al.		x	x							
	Chuah et al.	x									
	Genre et al.		x								
	Egbu, C. O.[13]		x								
	Holm, M. G.		x								
	Juodis et al.			x							
	Ürge-Vorsatz , & Novikova	x		x							
	Gynther et al.			x							

Type of document	Authors	Words									
		Retrofit	**Refurbish**	**Renovate**	**Upgrade**	**Renewal**	**Repair**	**Restore**	**Modernise**	**Convert**	**Rehabilitate**
Articles	Feist et al.										x
	Hoppe et al.	x		x							
	Thomsen, A.		x	x			x				
	Horsley et al.		x								
	Birkeland, J.	x									
	Balaras et al.	x	x	x			x				
	Ravetz, J.	x	x	x	x						
	Bellomo, & Pone	x									
	Gaterell, & McEvoy		x								
	Castleton et al.	x	x				x				
	Al-Homoud, M.	x									
	Crawley et al.	x									
	Bojić et al.	x	x	x							x
	Hong et al.	x									
	Pernodet et al.		x								
	Schwartz, & Raslan		x	x							
	Caccavelli, & Gugerli	x	x								
	Caccavelli, & Genre	x	x				x				
	Jaggs, & Palmer[14]	x	x								
	Li et al.	x									
	Stazi et al.	x									
	Crosbie et al.	x		x							
	Malatji et al.	x		x							
	Amstalden et al.	x		x		x					
	Higgins et al.	x									
	Fluhrer et al.	x									

Type of document	Authors	Words									
		Retrofit	**Refurbish**	**Renovate**	**Upgrade**	**Renewal**	**Repair**	**Restore**	**Modernise**	**Convert**	**Rehabilitate**
Reports	Hermelink, A. H.			×							
	Hermelink, & Muller			×							
	Tofield, & Ingham	x	x	x							
	Deutsche Energie-Agentur			x	x				x		
	Loga et al.		x	x				x	x		x
	Concerted action	x	x	x	x	x	x	x	x	x	x
	Jagemar, & Olsson	x	x	x					x		x
	OECD	x	x	x	x						
	Sagia et al.	x			x						
	Rhoads[15]	x	x								
	BPIE	x		x							
	BPIE	x	x	x	x				x		x
	BPIE	x		x	x						
	Næss-Schmidt et al.	x	x	x	x						
	Enerdata	x									
	Ministry of the Interior and Kingdom relations			x							
	Eichhammer et al.	x	x	x					x		x
	Neumann et al.	x	x	x							
	Waide, P.[16]	x	x	x							
	McGraw-Hill Construction	x		x					x		
	Empty homes agency		x								
	Klinckenberg et al.	x	x	x							

Type of document	Authors	Words									
		Retrofit	Refurbish	Renovate	Upgrade	Renewal	Repair	Restore	Modernise	Convert	Rehabilitate
Reports	DCLG	x									
	WBCSD	x	x	x	x						
	WGBC	x	x	x	x						
	IEA (2010)	x									
	IEA (2011)	x	x	x							
	Itard et al.[17]	x	x	x	x	x	x	x	x		x
	Stafford, A.	X	x								
	Neuhoff et al.	x									
	Dennehy, & Howley	x			x						
	T'Serclaes, P.		X								
	IEA (2008)	x	x	x	x	x		x			
	Paulou et al.	x	x	x							
	Bertoldi et al.			x							
	Rademaekers et al.	x	x	x							
	Boermans, & Bettgenhäuser	x		x							
	BioRegional Development Group	x									
	Loga, & Diefenbach		x								
	Zweifel, G.	x		x							
Brochures	CADmeleon	x									
	Ecofys	x		x							
	Minergie		x	x							
	Lapillonne, Pollier & Sebi	x									
	Lapillonne, Pollier, Sebi, & Mairet	x									
	EST	x	x								
	IPHA	x	x	x							
	E2Rebuild	x									

Type of document	Authors	Words									
		Retrofit	Refurbish	Renovate	Upgrade	Renewal	Repair	Restore	Modernise	Convert	Rehabilitate
Thesis	de Wilde, P.			x							
	Broin, E.	x		x							
	Dijkstra, L.			x		x					
	Boterenbrood, A. J.		x	x							
	Kouloumpi, I.	x	x	x							
	Heijder, J.	x	x	x							
	Staats, M.	x	x	x							
	Prevost, G.[18]	x		x						x	
Books	Friedman, A.	x	x	x							
	Burton, S.	x	x	x	x	x		x			x
	Thorpe, D.	x	x	x	x				x		
	Santín, O.		x	x							
	Concerted Action	x	x	x	x						
Legislation	European Parliament 2002			x							
	European Parliament 2010	x	x	x							
	Franconi et al.	x	x	x							
	Ball et al.		x	x	x	x		x	x		x
Other	ECEEE	x	x	x							

Words	Retrofit	Refurbish	Renovate	Upgrade	Renewal	Repair	Restore	Modernise	Convert	Rehabilitate
Total	104	78	82	23	9	8	8	12	6	12

Definitions:

1. Zhai et al.

The authors provide a definition of the term retrofit indirectly by distinguishing between deep energy and conventional retrofit. They define a deep energy retrofit as a “retrofit to increase building energy efficiency that uses integrative design to improve the economics of efficiency and achieve bigger energy savings at equal or lower cost, driving much larger energy savings (more than 50%) than conventional, isolated energy retrofits.

2. Ma et al.

The authors use the words retrofitting and refurbishment as synonyms stating the following: “(...) energy use in existing buildings can be reduced significantly through proper retrofitting or refurbishment, which is described as work required to upgrade an aged or deteriorated building”.

3. Ahern et al.

The authors define retrofitting as an “extensive thermal refurbishment” and use the word retrofit much more often throughout the article in comparison with the word refurbish.

4. Thuvander et al.

The authors provide the analysis of a literature review similar to the one presented here. They agree that there are many terms used in the literature, which have a large span of interpretation, and that are no universally agreed definitions of those terms. They conclude by stating that “we are using the commonly used term renovation, which we define to include middle range to major interventions”.

5. Menassa, C.

The author defines sustainable retrofit as follows: “Sustainable retrofit is a capital improvement with an associated cost that resets the building life, improves performance, and makes the building's use more predictable for an extended period of time”.

6. Rysanek, & Choudhary

The authors give a clear definition of the difference between conventional and deep-energy retrofit: “Though the terminology may differ regionally, building energy retrofits can be often classified into two types of endeavours: conventional and ‘deep-energy’ [7]. Similar to new building constructions, deep-energy retrofits are considered large-scale refurbishments that make significant alterations to a building’s architectural design, componentry, and operations towards effecting major energy savings (upwards of 50%). Conventional retrofits are comparatively smaller in scale and cost. They focus primarily on replacing only one or a few technologies in a building, such as an ageing boiler or inefficient glazing, to achieve a modest reduction of energy consumption or greenhouse gas emissions (approximately 15–25%)”.

7. Huang, & Hsueh

After recognizing that there many definitions of the term refurbishment by researchers, the authors define their concept of the word: “In this paper, refurbishment is defined as “the refurbishment behavior taken for the customers to extend the service life of buildings after completion of construction. It covers the following aspects: (1) maintenance and servicing of construction equipment, (2) breakdown maintenance, (3) improvement of indoor housing quality and space modification.”

8. Dascalaki, & Balaras

The authors define renovating as “repairs and restorations to good condition” and refurbishing as “upgrading to better condition”.

9. Alanne, K.

The author defines renovation, retrofitting and refurbishment as follows: “The concept ‘‘renovation’’ is usually divided under two categories: retrofit and refurbishment. The concept ‘‘retrofit’’ is generally used to identify actions that are required to bring a building into the framework of new requirements. The purpose of ‘‘refurbishment’’, instead, is to bring a building back to its original state”.

10. Juan et al.

The authors state that “Refurbishment work involves improvement, upgrading, renovation, retrofit, and repair of existing housing”.

11. Flourentzou & Roulet

The authors define refurbishment as the “work that will bring back the building to its original state” and retrofit as the “work that will upgrade the building to new requirements”.

12. Kolokotsa et al.

The authors define refurbishment and retrofitting as follows: “The term refurbishment implies the necessary modifications in order to return a building to its original state, while retrofit includes the necessary actions that will improve the building’s energy and/or environmental performance”.

13. Egbu, C. O.

The author gives a clear definition of refurbishment: “In this paper, refurbishment means works such as improvement, adaptation, upgrading, renovation, rehabilitation, modernization, conversion, retrofit, and repair; carried out on existing buildings for a variety of reasons. This definition, however, excludes works carried out on a routine basis such as cleaning, painting and decorating, and also emergency maintenance work.”

14. Jaggs, & Palmer

Under the *Energy Performance Indoor Environmental Quality Retrofit* (EPIQR) methodology, retrofit actions are defined as the “ones which upgrade and improve the building (or building element) to a higher standard than was originally planned for the apartment building”.

15. Rhoads, J.

The author refers to “low carbon retrofit” and defines it as follows: “incremental improvements to the building fabric and systems with the primary intention of improving energy efficiency and reducing carbon emissions”. The author also adds that the given definition excludes “disruptive refurbishment that would require the building to be vacated for an extended time, behavioural training programmes and space rationalisation or utilisation”.

16. Waide, P.

The author makes use of “sustainable refurbishment” and states that it is “what is required to achieve sustainable housing, the definition of which was agreed at the Genval conference”. The author also makes use of the word retrofit to express single energy efficient interventions.

17. Itard et al.

The authors assign a wide scope to the term renovation: “renovation activities may vary from demolishing entire buildings to simple maintenance activities”.

18. Prevost, G.

After a brief literature review on the words retrofitting and adaptation, the author states: “While it is true that ‘retrofitting’ and ‘adaptation’ embody the same spirit, they will be used to denote larger projects and smaller projects respectively. When a term is needed to embody both retrofitting *and* adaptation, the phrase ‘retrofitting the suburbs’ or ‘suburban retrofitting’ will be used”.

Appendix II. List of Decision Support Systems for specific retrofit measures

DSSs designed to analyse specific retrofit interventions, such as “green roofs”, solar energy or HVAC systems were not considered for the selection of DSSs for the present research, since they lack a whole building approach and are thus too specific. Nevertheless, those DSSs for specific retrofit interventions found during this research are hereby presented.

SPOT™

Full name: Sensor Placement + Optimization Tool

Description: This DSS aids in the design of lighting and optimization of day lighting both for retrofit of existing lighting systems and for new buildings. It helps establishing the optimal photo sensor placement and system settings for a given space by providing the analysis and comparison of different scenarios.

Developer: Daylighting Innovations (US Private company)

Website: http://www.daylightinginnovations.com/spot-home

SolTerm

Full name: Performance analysis of solar systems

Description: The DSS is used to calculate the performance of solar thermal and photovoltaic systems. It performs the simulation of the annual energy balances of the building and provides an economic and environmental analysis. It also provides the established analysis to apply to Governmental subsidies.

Developer: National Laboratory for Energy and Geology (Portugal)

Website: http://www.lneg.pt/iedt/projectos/370/paginas/69

HERO

Full name: HVAC Energy Reporting and Optimisation

Description: HERO is a web-based software DSS developed to analyse the energy performance of the HVAC system at use. It monitors the performance of the HVAC system during a period of time, produces reports of the energy performance and compares the system against the benchmark. Through that analysis, it provides retrofit options in order to improve the system along with its economic and energy impacts.

Developer: iSERVcmb Project (monitoring available for the EU-27)

Website: http://www.iservcmb.info/

Cool Roofs Toolkit

Description: It is a web-based DSS that evaluates the benefits of installing a “cool roof” and compares them to the performance of the existing roof in the building. It calculates the annual energy savings for heating and cooling. The DSS is free and available for the EU countries.

Developer: DSS developed under the “Cool Roofs” project within the IEE Programme

Website: http://pouliezos.dpem.tuc.gr/coolroof/coolcalcenergy_eu.html

Parasol

Description: The DSS simulates the energy demand and the peak loads for heating and cooling for different types of glazing and shading devices. The DSS can be used to both the design and retrofit phases and both for services and residential buildings.

Developer: Faculty of Engineering, Lund University

Website: http://www.ebd.lth.se/english/software/parasol/

Appendix III. Original table presented by Staats (2013)

The model used in Section 6.3 to compare the DSSs from the perspective of the user was adapted from the model developed by Staats (2013). Table 22 presents the parameters, weights and benchmarks for each innovation characteristic, originally presented by the author and that was further adapted for the present research.

Table 22 - Parameters, weights and benchmarks for each innovation characteristic as presented by Staats (2013).

Table 1: Parameters, weights and benchmarks as identified

Innovation characteristic	Parameter	Sub-parameter	Weight	Benchmark
Relative advantage				
	Clear information regarding options	Specific renovation options proposed	3	Options appear clearly in tool and have clear descriptions, subjective description
	Clear beneftis	Financial	3	Savings in €/year, savingpercentage, total investments and/or Pay Back Time (PBP)
		Energetic	3	Savings in kWh and/or m3 natural gas per year and/or square meters
		Environmental	3	Savings in ton CO2/year
		Health	3	Increased comfort, better indoor climate, less grid dependence
	Specifitiy of input	Detail of input requested	3	Specific amounts (kWh), approximations (10-50 kWh, 60-100 kWh etc.) or subjective groups (low, normal, high)
	Possibility to run different scenarios		2	Amount of scenarios able to run together, able to run for different types of users
Compatability				
	Software source		4	Web (usable with Internet Explorer, Firefox and Chrome) Excel Third party software
	Standard dutch inputs		3	m3 natural gas/kWh electricity/....
	Usage of EU labels	Input usage	1	Input usage of EU label
		Output usage	2	Output usage of EU label
	Easy to understand design	Clear lay-out	3	Immediate comprehension of lay-out
		Clear navigation	3	Immediate comprehension of what indicators to fill in and how to evoke the analysis
Complexity				
	Complexity of input		4	Amount of input variables needed
	Complexity of output		4	Amount of output variables received
	Logical input descriptions		3	Subjective description
	Logical output descriptions		3	Subjective description
	Possibility of explaination/help function		4	Availability and profoundness of explaination/help function
Trialability				
	Easiness of adjustments		2	After the first sequence adjustments to inputs can be made instantly
	Availability	Free/Demo version/Paid version	3	Price in €; demo version usage in weeks
Observability				
	Can be found on the internet	Using Dutch keywords: 'renovatie', 'gebouwen', 'energie' , 'besparing', 'Nederland' and 'software'	4	Software within the first page
		Using title/name of software as keywords	3	Software within the first 3 links
	(Succesfull) cases found which refer to this DSS		4	Search on google using title/name of software as keywords
	Attractive design		3	Subjective description

Appendix IV. Figures of the innovation characteristics in the DSSs

The present appendix shows the figures mentioned in the results of the comparison of the innovation characteristics (see Section 6.4).

Innovation characteristic: Compatibility

Sub-parameter: Software source

Figure 15 - *Generation* incompatibility with different MS Windows versions.

Innovation characteristic: Compatibility

Sub-parameter: Software errors

Figure 16 - *Retrofit Advisor* error when activating macros.

Financial factors	Unit	Actual State	Repair
Net rent adjustment (including energy cost reduction)	%		
Periodic costs, total	€/		3
Capital costs	€/Year	23.400	2
Administration costs (fees, dues, taxes)	€/Year	8.293	
Service and disposal costs (without energy)	€/Year	336	
Repair and maintenance cost (incl. house keeping)	€/Year	5.880	
Tax reductions	€/Year	5.040	
Costs (singular)	€		23
Fees, charges	€		2

Unterhalts-, Betriebs- und Kapitalkosten, die jährlich anfallen

Figure 17 - *Retrofit Advisor* bug: help to fill in the input is presented in German although English was selected.

Innovation characteristic: Compatibility

Parameter: Usage of EU Building energy label

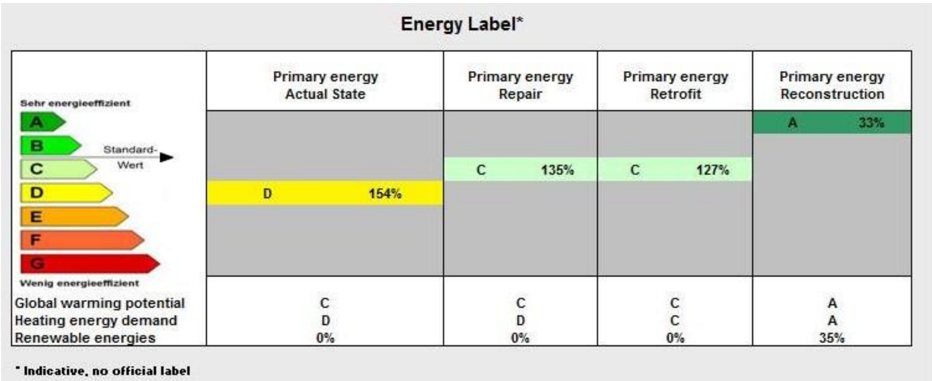


Figure 18 - EU building energy label for current situation and retrofit scenarios in *Retrofit Advisor*.

CALIFICACIÓN 33,2 E

Elemento	%
Opacos	46,00%
Semitransparentes	7,60%
Ventilación	27,60%
Puentes térmicos	7,70%
Carga interna	2,00%
ACS	9,10%

Figure 19 - EU building energy label presented by *ICE (2.0.8)* for the current situation.

Innovation characteristic: Compatibility

Parameter: Interface design

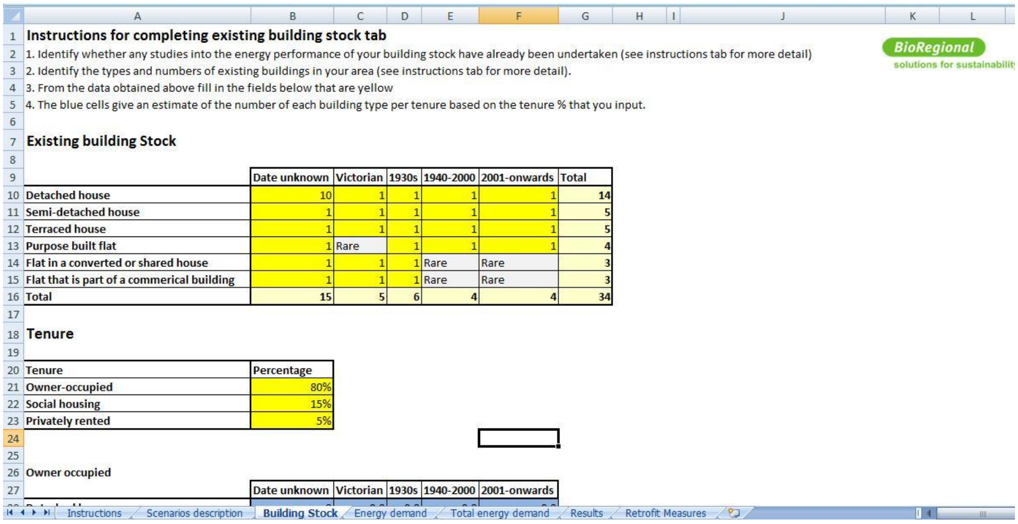


Figure 20 - Interface design of *BioRegional*.

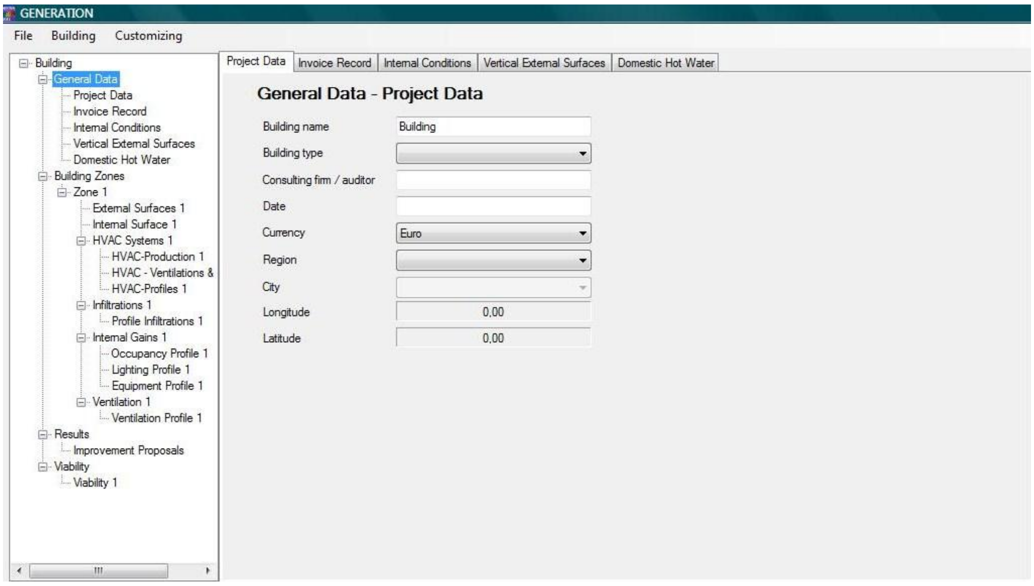


Figure 21 - Interface design of *Generation*.

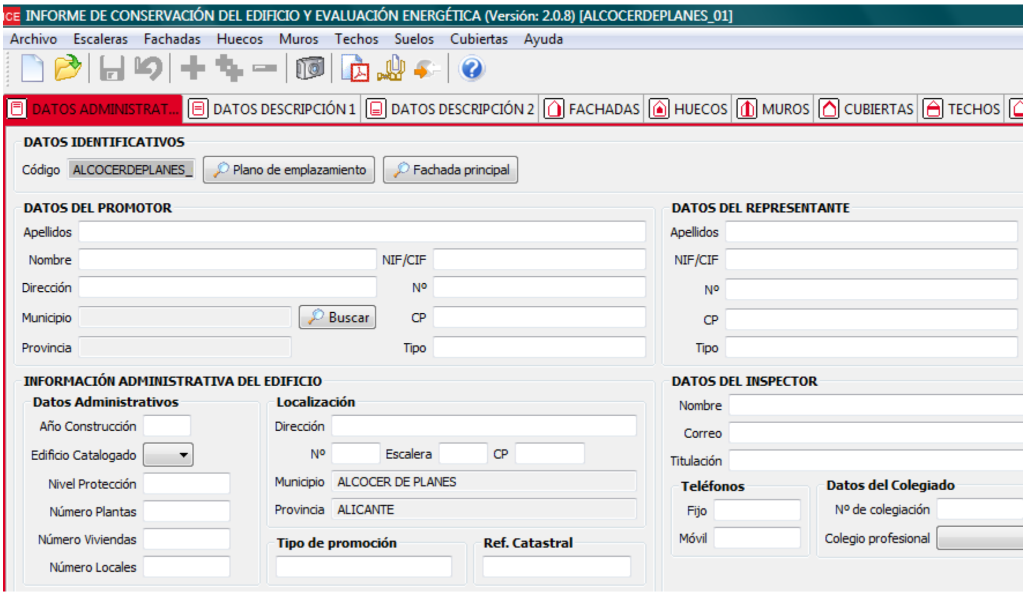


Figure 22 - Interface design of *ICE (2.0.8)*.

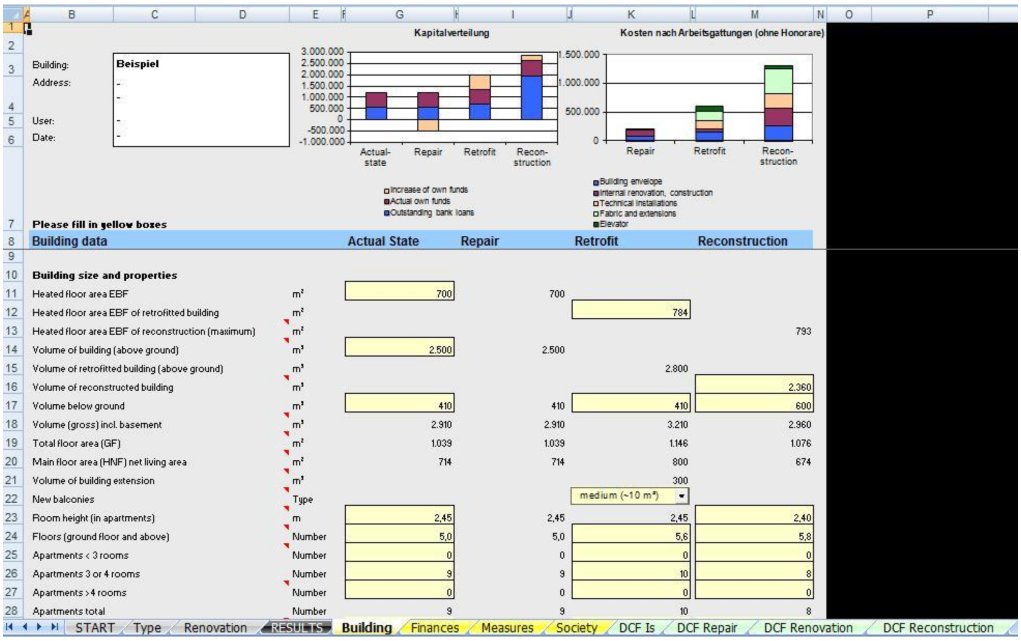


Figure 23 - Interface design of *Retrofit Advisor*.

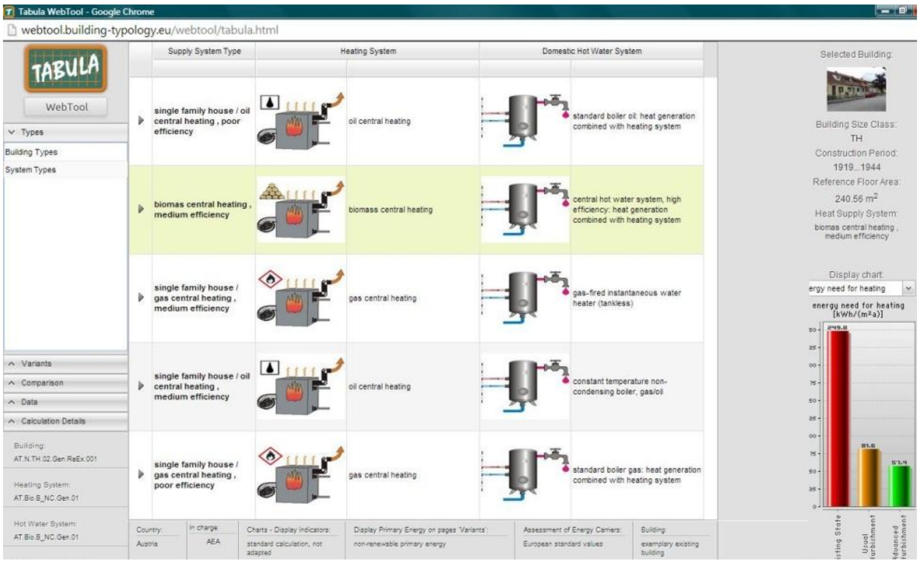


Figure 24 - Interface design of *TABULA*.

Innovation characteristic: Complexity

Parameter: Complexity of input and output

Baseline energy demand per dwelling

Average energy demand values for heat and electricity are provided below. If you have your own d

The associated CO2 emissions from the current energy demand is calculated for you, but you can ch

Use standard data

Heat demand per dwelling (domestic hot water + space heating)

	Date unknown	Victorian	1930s	1940-2000	2001-onwards
Detached house	22.221	33.658	23.746	22.704	8.776
Semi-detached house	17.777	26.926	18.997	18.163	7.021
Terraced house	14.972	23.624	16.368	14.348	5.546
Purpose built flat	9.766	Rare	12.400	11.791	5.106
Flat in a converted or shared house	8.539	11.528	5.550	Rare	Rare
Flat that is part of a commerical building	8.369	11.528	5.210	Rare	Rare

Electricity demand per dwelling

	Date unknown	Victorian	1930s	1940-2000	2001-onwards
Detached house	8.477	7.895	8.753	8.829	8.431
Semi-detached house	6.782	6.316	7.002	7.063	6.745
Terraced house	5.789	5.541	5.796	6.492	5.328
Purpose built flat	5.473	Rare	5.200	5.200	6.020
Flat in a converted or shared house	5.962	5.408	6.515	Rare	Rare
Flat that is part of a commerical building	5.962	5.408	6.515	Rare	Rare

Figure 25 - Example of the amount of input asked by *BioRegional*.

Total housing stock

Scenario		% CO2 saved	Energy bill saving (£/yr)	Cost (£)	£/kgCO2e	Pay back period (years)	Remaining CO2 emissions
Retrofit	Full retrofit	62%	£33.203	£1.476.266	9	44	98.530
	Light retrofit	38%	£20.184	£139.586	1	7	162.884
Connecting to a district heating network	Energy from waste	57%	no change	£307.182	2	14	113.219
	Waste heat	46%	no change	£325.208	3	14	142.289
	Natural gas CHP & natural gas back-up	47%	no change	£362.236	3	16	139.472
	Biogas CHP & natural gas back-up	94%	no change	£357.584	1	16	16.590
	Biomass CHP & natural gas back-up	47%	no change	£360.478	3	16	139.300
Combination: retrofit & connecting to a district heating network	Energy from waste	67%	£20.184	£446.768	3	11	87.353
	Waste heat	57%	£20.184	£464.795	3	11	113.453
	Natural gas CHP & natural gas back-up	57%	£20.184	£501.822	3	12	112.620
	Biogas CHP & natural gas back-up	94%	£20.184	£497.171	2	12	15.072
	Biomass CHP & natural gas back-up	61%	£20.184	£500.064	3	12	102.795

Figure 26 - Amount of output retrieved by *BioRegional*.

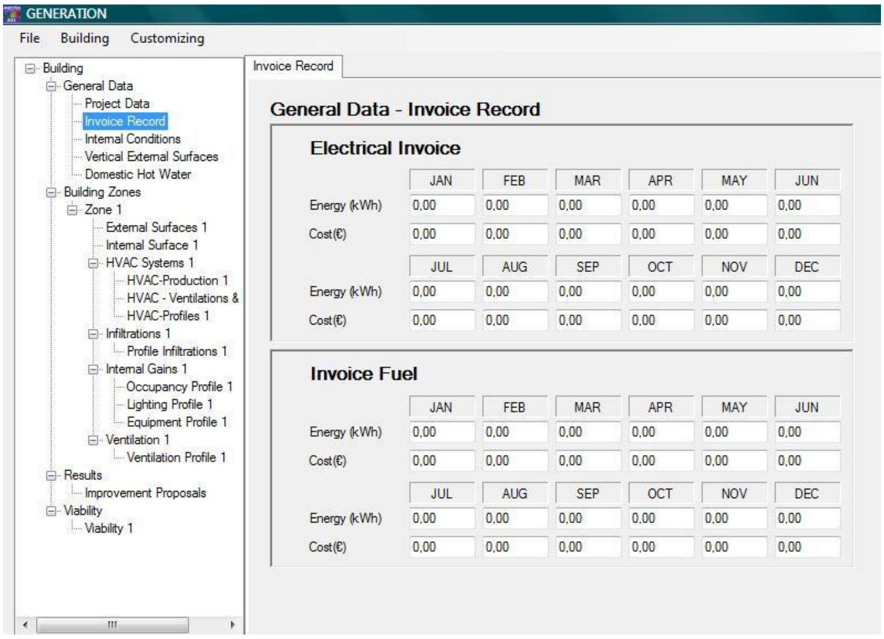


Figure 27 - Amount of input asked by *Generation*.

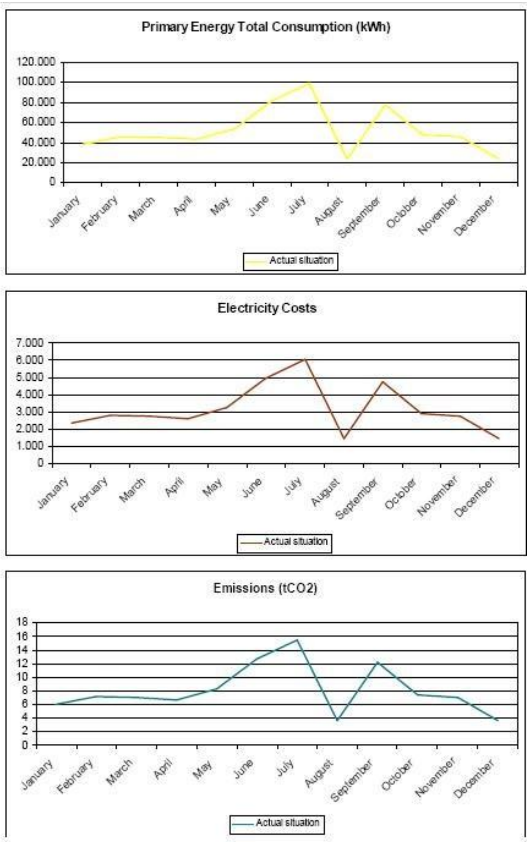


Figure 28 - Example of the graphic output retrieved by *Generation*.

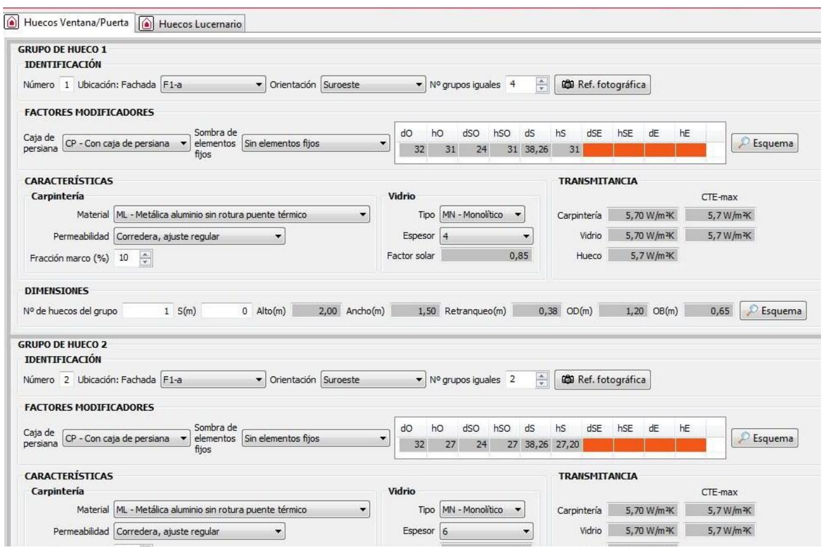


Figure 29 - Example of the amount of input regarding the windows of the building in *ICE (2.0.8).*

Figure 30 - Example of the amount of output retrieved by *ICE (2.0.8)*.

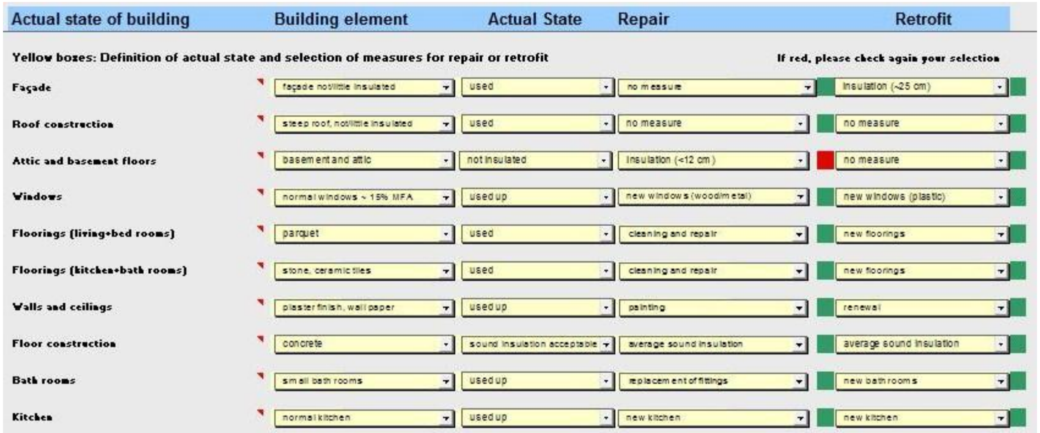


Figure 31 - Example of the amount of input variables asked by *Retrofit Advisor*.

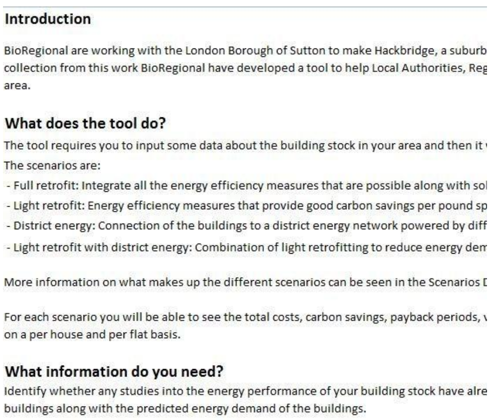
Figure 32 - Example of the amount of output variables retrieved by *Retrofit Advisor*.

Figure 33 - Example of input asked (typologies selection) by *TABULA*.

Figure 34 - Example of output graphic results of *TABULA*.

Innovation characteristic: Complexity

Parameter: Help function


Introduction

BioRegional are working with the London Borough of Sutton to make Hackbridge, a suburb
collection from this work BioRegional have developed a tool to help Local Authorities, Reg
area.

What does the tool do?

The tool requires you to input some data about the building stock in your area and then it
The scenarios are:
- Full retrofit: Integrate all the energy efficiency measures that are possible along with sol
- Light retrofit: Energy efficiency measures that provide good carbon savings per pound sp
- District energy: Connection of the buildings to a district energy network powered by diff
- Light retrofit with district energy: Combination of light retrofitting to reduce energy dem

More information on what makes up the different scenarios can be seen in the Scenarios [

For each scenario you will be able to see the total costs, carbon savings, payback periods,
on a per house and per flat basis.

What information do you need?

Identify whether any studies into the energy performance of your building stock have alre
buildings along with the predicted energy demand of the buildings.

Figure 35 - Example of the instructions to work with *BioRegional* given in the interface of the DSS.

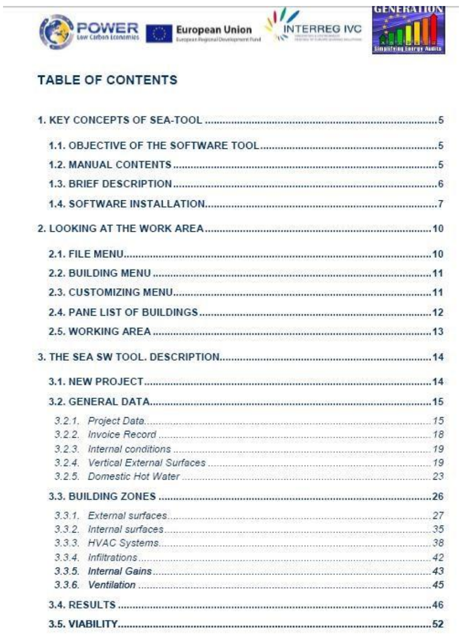


TABLE OF CONTENTS

Figure 36 - Excerpt of the table of contents of the user guide of *Generation*.

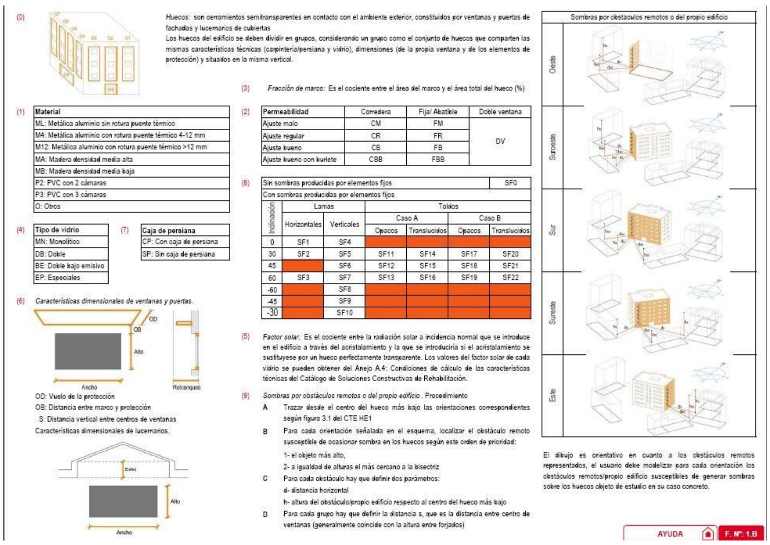


Figure 37 - Help function regarding input of windows in *ICE (2.0.8)*.

Building valuation and financial rating

The value of the property before and after renovation can easily be estimated and compared with the data-sheets "Building", "Finances" and "Measures". Only the yellow boxes have to be filled in. All other data is automatically calculated. Changing boundary conditions, such as credit rates, can be easily adapted and reconsidered.

Environmental impact and social evaluation

Besides the financial calculation also the environmental impact and the social impact of the retrofit measures are evaluated according to an individual valuation. The Retrofit Advisor allows the compare economical facts with environmental and social aspects.

RESULTS: Recommended renovation strategies

The final analysis (data sheet "RESULTS") allows to compare the financial aspects with the personally weighted consideration of environmental and social aspects. The recommended renewal strategy is based on the data given by the user, but also by numerous default values given by the program. The recommendation by the Retrofit Advisor should be considered as an advice that finally always should be checked by a refurbishment specialist.

On top of each data sheet, the most relevant results are graphically presented for direct information. They allow a rapid evaluation of entered data.

For professionals

There are additional data-sheets for professionals. The data sheets "DFC Is", DFC Repair "DFC Renovation and "DFC Reconstruction" allow a more detailed financial evaluation based on the "Discounted Cash Flow" DFC method. The Discounted Cash-Flow method calculates the value of the building based the expected service life and the yearly assumptions for the inflation, for interest, for service cost and so on. Empirical data is used as defaults for the average user.

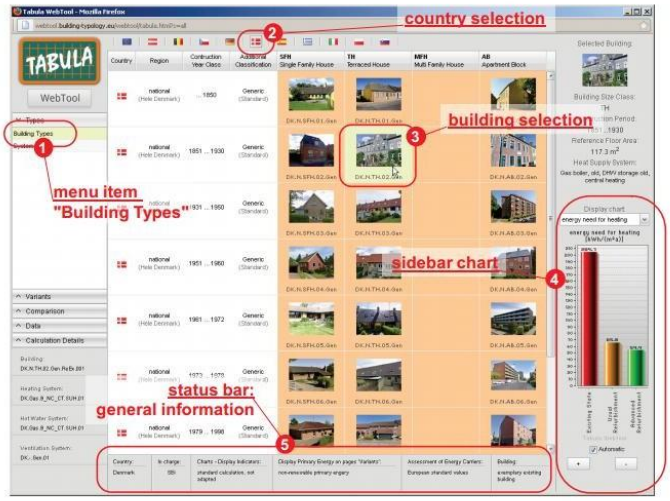
Attention: The Retrofit Advisor was not developed for the evaluation of non-residential buildings, protected historical buildings, or single family homes.

The actual version of the Retrofit-Advisor (03.2011) is a development version of the program, which still may contain errors. A support of the program is only very limited possible. Suggestions, desires and improvement suggestions are desired to following contact address.

Recommendations, wishes or proposals for improvements are welcome to the following contact address.

Figure 38 - Instructions to work with *Retrofit Advisor* given in the first sheet of the MS Excel DSS.

2 Country and Building Selection



The webtool always starts at the menu item "Building Types" ❶. At this page a country can be selected by click on the respective flag ❷. All those countries are listed for which a building typology on the basis of the TABULA definitions has been elaborated.

Figure 39 - Overview of the User Guide of *TABULA*.